UNIVERSITY OF PETRA

كلية العمارة والتصميم
Faculty of Architecture & Design

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

ASCAAD 2023

NOVEMBER 7-9 2023
UNIVERSITY OF PETRA
AMMAN, JORDAN

11th International Conference of the Arab Society for Computation in Architecture, Art and Design

C+ + + : Computation, Culture, and Context

EDITED BY
SHERIF ABDELMOHSEN | AMER AL-JOKHADAR

PROCEEDINGS

The 11th International Conference

of the Arab Society for

Computation in Architecture, Art and Design

HYBRID CONFERENCE

7 – 9 November 2023

Amman, Jordan

Faculty of Architecture and Design

University of Petra (UOP)

EDITED BY

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ASCAAD DECLARATION

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

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CONFERENCE HOST

The conference is hosted by the Faculty of Architecture and Design, at University of Petra (UOP), Amman, Jordan. Established in 1991, the Faculty carries a creative message for the distinguished advancement of architecture and design, and in keeping with the latest achievements in human civilization. The Faculty offers 5 Bachelor programs (Architecture, Interior Design, Graphic Design, Animation and Multimedia, and Digital Film Design Technology). It also offers two Master Programs (Interior Design, and Sustainable Smart Cities). In 2022, the Faculty achieved the Jordanian Quality Assurance Certificate for 4 years, issued by the Commission for Accreditation and Quality Assurance of Higher Education Institutions. The Faculty hosts a number of facilities, including the Learning Resources Lab, Lighting and Acoustics Lab, Silk Screen Lab, Ceramics Lab, Photography Lab, Model Making Workshop, Fine Arts Studio, Carpentry and Metal Workshop, and a large exhibition hall for students' work. Moreover, the Faculty has been engaged in international research projects with UCL, Oxford, Reading, Berlin and Brighton universities, and received the Newton Fund Prize 2020. Also, students from the five departments have constantly won national and international prizes. The Faculty of Architecture and Design collaborates with other faculties in the university, including Faculty of Engineering (Civil Engineering Department), Faculty of Information Technology (Virtual and Augmented Reality Department), and Faculty of Mass Communication. With the development of e-learning, e-library, and high-speed communication facilities, UOP has transformed itself into a smart campus where students and faculty interact with knowledge to develop their state-of-the-art skills with an aim towards enhancing entrepreneurship, innovation, and creativity.

ABOUT ASCAAD

The Arab Society for Computation in Architecture, Art and Design (ASCAAD) is a society of those who teach, conduct research and practice in computational design in the Arab World regions of West Asia, and North Africa. ASCAAD is also active in Central Asia, Sub-Sahara Africa, and the Mediterranean.

ASCAAD is one of five regional sister organizations that promote computational design research and education worldwide, including *ACADIA* (North America), *eCAADe* (Europe), *SIGraDi* (Latin America), and *CAADRIA* (Asia), in addition to the global *CAAD Futures* organization.

ASCAAD aims to facilitate communication and information exchange regarding the use of computational design technology in architecture, planning, building science, and the arts, that are dramatically challenging our fundamental assumptions, theories, and practices of conventional design paradigm. Since 2005, the society has been holding conferences and educational events that are hosted by a different university each time. The output of the conferences and contributions from the educational events are published as a Conference Proceedings book.

تضم الجمعية العربية للحوسبة فى العمارة والفنون والتصميم (أسكـاد) الباحثين والمهتمين بمجال العمارة والفنون والتصميم بمساعدة الحاسب الآلى في العالم العربي من غرب آسيا وشمال إفريقيا، بالإضافة إلى آسيا الوسطى وجنوب الصحراء الكبرى فى أفريقيا ومنطقة حوض البحر الأبيض المتوسط.

وتعتبر الجمعية العربية للحوسبة فى العمارة والفنون والتصميم (أسكـاد) واحدة من خمس هيئات إقليمية مماثلة فى مجال أبحاث وتعليم التصميم الحوسبى عالميا والتى تتضمن هيئة أكاديا (أمريكا الشمالية)، إيكادى (أوروبا)، سيجرادى (أمريكا اللاتينية)، وكادريا (آسيا)، بالإضافة إلى هيئة كاد فيوتشرز الدولية.

وتهدف جمعية أسكاد إلى تسهيل التواصل وتبادل المعلومات فيما يتعلق باستخدام تكنولوجيا التصميم الحوسبى في مجالات العمارة والتخطيط وعلوم البناء والفنون والتي تتحدى بشكل كبير افتراضاتنا ونظرياتنا وممارساتنا لنموذج التصميم التقليدي. وقد عقدت الجمعية منذ عام ٢٠٠٥ العديد من المؤتمرات والفعاليات التعليمية التي تستضيفها جامعة مختلفة في كل مرة، ويتم نشر مخرجات المؤتمرات والمساهمات من الفعاليات التعليمية ككتاب وقائع مؤتمر.

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PREFACE

This book comprises the Proceedings of the 11th International Conference of the Arab Society for Computation in Architecture, Art and Design (ASCAAD 2023), held as a hybrid event from 7th November 2023 to 9th November 2023, at the Faculty of Architecture and Design, University of Petra, Amman, Jordan. The proceedings contain the 57 accepted papers. All papers are also available digitally at CumInCAD (Cumulative Index of Computer Aided Architectural Design) – http://papers.cumincad.org.

Conference Theme

The ASCAAD 2023 theme focuses on **Computation, Culture, and Context**; a triad that is increasingly informing and reshaping the emerging dynamics of design and construction in the built environment of several regions in the Global South. Socio-cultural spheres, heritage roots, contextual relevance, and art and material culture have historically been the primary sources for design and construction innovation and uniqueness in such regions and contexts. Complex geopolitical events however have resulted in a shift towards a perplexed practice of post-modernist styles or imported Western models of design and production, coupled with some attempts to rebrand modernist and post-modernist approaches through critical regionalism and revolts against orientalist movements.

Technology and computation have always been an active factor and tool in reflecting these practices. Advancements in computational design have in some ways sparked a latent intent to revive the character and heritage of rich civilizations. While this has led to growing interest within communities belonging to such rich history to adopt computational methodologies and practices, it has equally raised questions regarding authenticity, innovation and identity. Many of the recent attempts to shift away from Western-centered orientalist approaches have in reality not been that far, but have often further accentuated the superficial use of geometrical practices and pattern-based approaches in art, architecture, and urban design, characterized by stereotypical schemes in building interiors, façade screens, and spatial configurations.

With lots of potential for growing research in this area at the intersection of computation, culture, and context in architecture, art and design, the need to address such a theme has become imminent. This year, the Faculty of Architecture & Design at the University of Petra (UOP), Jordan, will host the 11th ASCAAD international conference in order to primarily question the emerging role of computation within socio-cultural contexts and to discuss novel ideas and design approaches in this area, with the prospect of developing culturally and contextually conscious approaches in the built environment using state-of-the-art computational design methods and practices, and offering solutions to researchers, architects, designers, artists, educators, and technologists whose positions are at the intersection of avant-garde integration of technology in design on one hand, and rootedness and authenticity of culture and heritage on the other.

Conference Topics

1) **Digital Heritage and Culture**
   - Photogrammetry
   - Digital Heritage and Culture
   - Heritage BIM
   - Preservation of Historic Sites
   - Virtual Museums
   - Mapping Refugees and Marginalized Communities

2) **Smart Cities and Buildings**
   - Smart Virtual Cities
   - Cities Modeling, GIS and Smart Planning
   - Responsive Architecture and Internet of Things
   - Smart Infrastructure and Transportation
   - Urban Analytics and Modeling of Virtual Cities
   - Big Data Management in Architecture and Urban Design

3) **Building Informatics and Parametrics**
   - Building Information Modeling and Management
   - Algorithmic Thinking and Parametric Systems
   - Machine Learning in Architecture and Construction
   - Digital Twinning and Internet of Buildings
   - Advanced Digital Manufacturing and Mass Customization
   - Material Culture in Design and Fabrication

4) **Digital Media and Generative Art**
   - 2D and 3D Animation
   - Gaming and Interactive Design
   - Infographic Design
   - Motion Graphics
   - Digital Applications in Advertising
   - Digital Film Design Technology and Cinematography

5) **Virtual Realms and Multiverse Environments**
   - Digital Representation and Visualization
   - Extended Reality (XR)
   - Human-computer Interaction
   - User Experience and Human Centered Design in the Metaverse
   - Multiverse Culture
   - Hybrid Spaces and Real-Time Collaborative Environments

6) **Performative-Driven Design and Digital Green**
   - Green BIM
   - Building Energy Management
   - Sustainable Urban Planning
   - Simulation for Low Carbon Design
   - Human-centered Simulation
   - Smart Building Systems

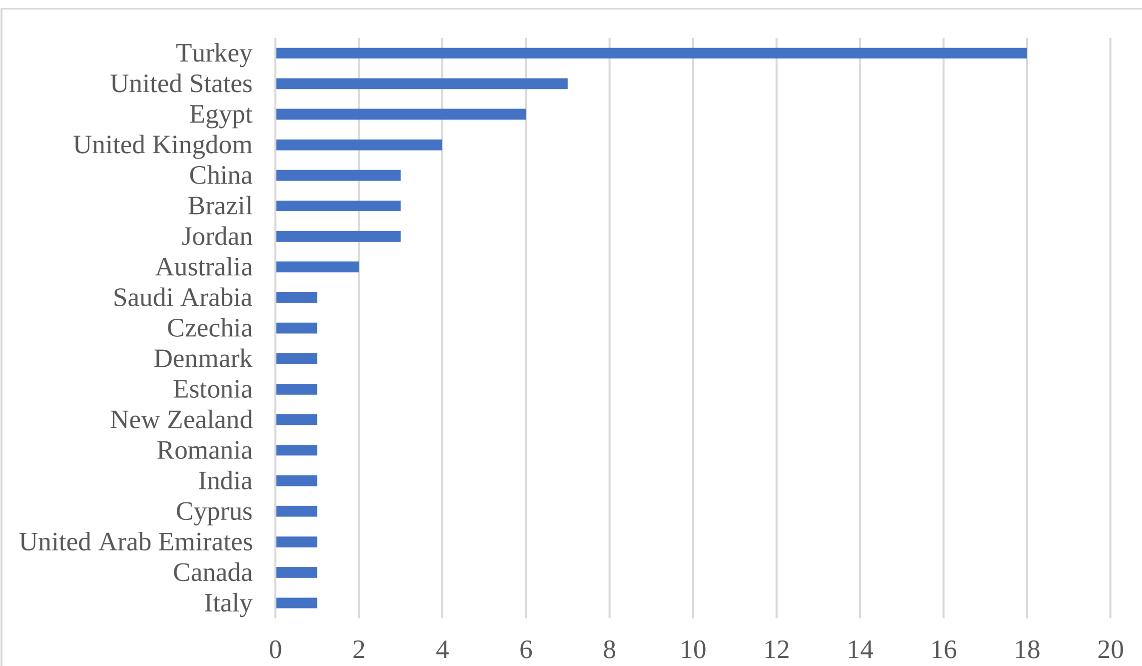
Submissions and Statistics

The conference theme of ASCAAD 2023 at the University of Petra (UOP) 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 **142 abstracts** representing **31 countries**. 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, **128 abstracts** were forwarded to the second round of the peer review process, where they were invited to submit their full paper submissions. This included one of two types of submissions:

1. Long papers (English or Arabic) that describe well-developed or completed research (max 4000-5000 words, or 14 pages of the ASCAAD 2023 template).
2. Short papers (English or Arabic) that describe research in progress (max 2500 words, or 10 pages of the ASCAAD 2023 template).

The ASCAAD 2023 scientific committee asked authors at this stage to include in their full paper English submissions an Arabic abstract. The committee provided support where needed for non-native Arabic speakers. 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 **75 expert referees** from around the globe.

A final number of **57 full papers** by **165 authors** representing **20 countries** from the Middle East, Europe, Asia, North America, South America, and Australia were identified by the ASCAAD 2023 scientific committee and were invited to submit camera-ready papers.



ASCAAD 2023 full paper submissions by country

Out of the 57 full-paper submissions, the following is the number and aspects of papers distributed on the six topics of the conference:

- 9 papers (**15.8%**) were more focused on "**Topic 1: Digital Heritage and Culture**", involving aspects related to photogrammetry, digital heritage and culture, heritage BIM, preservation of historic sites, virtual museums, and mapping refugees and marginalized communities.
- 6 papers (**10.5%**) were focused on "**Topic 2: Smart Cities and Buildings**", involving aspects related to city modelling, GIS and intelligent planning, responsive architecture and Internet of Things (IoT), smart infrastructure and transportation, urban analytics and modelling of virtual cities, in addition to big data management in architecture and urban design.
- 15 papers (**26.3%**) were focused on "**Topic 3: Building Informatics and Parametrics"**, involving aspects related to building information modelling and management, algorithmic thinking and parametric systems, machine learning in architecture and construction, digital twinning and internet of buildings, advanced digital manufacturing and mass customization, and material culture in design and fabrication.
- 5 papers (**8.8%**) were focused on "**Topic 4: Digital Media and Generative Art"**, involving aspects related to 2D and 3D animation, gaming and interactive design, infographic design, motion graphics, digital applications in advertising, and digital film design technology and cinematography.
- 12 papers (**21.1%**) were focused on "**Topic 5: Virtual Realms and Multiverse Environments"**, involving aspects related to a digital representation and visualization, Extended Reality (XR), human-computer interaction, user experience and human-centered design in the metaverse, multiverse culture, hybrid spaces and real-time collaborative environments.
- 10 papers (**17.5%**) were focused on "**Topic 6: Performative-Driven Design and Digital Green"**, involving aspects related to green BIM, building energy management, sustainable urban planning, simulation for low carbon design, human-centered simulation, and smart building systems.

The Hybrid Conference

The ASCAAD 2023 conference was hosted at the University of Petra (UOP) from November 7-9, 2023. Due to the regional circumstances, the organizing committee of the conference decided in the last few weeks to transition the conference format to a hybrid model. The six main conference topics were structured in 12 sessions that unfolded in two parallel sessions over the two days (November 8^{th} and November 9^{th}), preceded by two pre-conference workshops on November 7^{th}. This structure is also followed in the organization of the conference proceedings.

For the conference setup, the conference committee had asked all authors with accepted full-paper submissions to submit, in addition to camera-ready papers, a PowerPoint presentation and a 10-minute pre-recorded video of their presentations and their bios and affiliations. Each presenting author was allowed 10 minutes to give their live presentation, allowing for a 15-minute extended discussion moderated by session chairs. Live sessions were broadcast via Microsoft Teams. In the event of a no-show or technical challenge, the UOP IT team played the pre-recorded video presentations on behalf of the authors. Keynote speakers were hosted via Microsoft Teams.

Amer Al-Jokhadar
ASCAAD 2023 Conference Chair

WELCOME NOTE – THE UNIVERSITY OF PETRA (UOP), JORDAN

Your Excellency Professor Adnan Badran, The Supreme Chancellor of the University of Petra, and its Board of Trustees

Professor Rami Abdul-Rahim, President of the University of Petra

Ladies and Gentlemen, Esteemed Guests, Distinguished Colleagues, and Participants from around the World,

Good morning, and welcome to the 11th International Conference of the Arab Society for Computation in Architecture, Art, and Design (ASCAAD 2023), hosted by the University of Petra, Jordan. It is an immense pleasure and honor to stand before you today as the Dean of the Faculty of Architecture and Design, and the Chair of the Conference to launch this prestigious event.

At this critical time, we hope that the war against our brothers and sisters in Gaza will stop and be replaced by justice and peace. The organizing committee of the ASCAAD 2023 conference decided in the last few weeks to transition the conference format to a hybrid model.

Since the first day of establishment in 1991, our mission at the University of Petra has consistently aimed to serve as a prominent hub for culture, knowledge, scientific research, leadership, creativity, and innovation on both national and international levels.

ASCAAD 2023 is more than just a gathering of scholars, researchers, architects, designers, and artists; it celebrates intellectual curiosity, innovative ideas, and creative artistic expressions.

This year, we focus on the triple Cs: Computation, Culture, and Context, as we are targeting to discuss novel ideas, with the prospect of developing culturally and contextually mindful design approaches in the built environment, using state-of-the-art computational design methods and practices, and offering solutions to researchers, architects, designers, artists, educators, and technologists whose positions are at the intersection of cutting-edge technology integration in design on one hand, and authenticity of culture and heritage on the other.

Hosting this conference has been such a pleasure. After extensive preparations spanning over one year, we are deeply committed to providing a robust platform that facilitates the discourse of ideas, the sharing of knowledge and experiences, and the investigation of potential prospects.

Over two days, this conference will be a melting pot of perspectives, ideas, and insights. We have an impressive lineup of two keynote speakers, Professor Marcos Novak, and Dr Suleiman Alhadidi, two pre-conference workshops, and a total of 58 peer-reviewed paper presentations authored by 165 researchers from over 20 countries that promise to enlighten, inspire, and challenge your understanding of the intersection between computation, culture, and context.

As we gather here today, I encourage you to embrace the diversity of voices and experiences that ASCAAD 2023 offers. Engage in lively discussions, connect with your peers, and seize this opportunity to build new collaborations and partnerships.

I would like to thank Professor Rami Abdel-Rahim, the President of UOP, and Professor Faisal Aburub, the Dean of Scientific Research and Graduate Studies, for their continuous encouragement and support in hosting such activities and venues.

I would like to extend my utmost gratitude to Professor Sherif Abdulmohsen, the President of ASCAAD. Also, to the scientific and organizing committee, the sponsors, the reviewers, and all individuals who have dedicated their efforts to make this event a reality.

I have no doubt that ASCAAD 2023 will be a resounding success and a memorable experience for all of us. I wish you all a productive and enriching conference, and I hope you find inspiration to shape the future of architecture, art, and design.

Thank you and enjoy ASCAAD 2023

Amer Al-Jokhadar
Dean, Faculty of Architecture and Design
Head of the Department of Architecture
ASCAAD 2023 Conference Chair
University of Petra, Jordan

FOREWORD – ASCAAD

Dear ASCAAD friends,

The 11th International Conference of the Arab Society for Computation in Architecture, Art and Design (ASCAAD 2023) has invited scholars, researchers and students worldwide to address methodologies, approaches, and processes within the framework of computation, culture, and context. Since its inception in 2005, ASCAAD has thrived to become a forum and community for researchers, educators, scholars, and students working in the area of computational design in the Arab World or belonging to Arab origins, as well as West Asia and the Mediterranean. From the very first conference, ASCAAD has always been proud of its growing network and body of amazing researchers, scholars, students, and hosts, whom we owe tremendously the growth, strength and resilience of our society.

This journey has not been an easy one, with lots of ups and downs that our region is facing. It is especially crucial in these difficult and challenging times we are witnessing, and the hardships and atrocities our Palestinian brothers and sisters are unfairly facing on a daily basis, that we strengthen our bonds as a society, as a unified community, to demonstrate to ourselves first and foremost and to the world, that we are capable, that we can, that we can excel in the latest and greatest advancements in science, art, and technology, that we are collectively resilient, and that through our social, genuine and unique heritage, culture and context, we are stronger in the face of any challenges. If there is one silver lining to the ongoing troubling events in the region, it is that the ASCAAD community has come closer, and is on a positive trajectory to develop new energy, to stick to its roots, and to boost its resilient character.

This version of the conference is simply an exemplification and manifestation of that concept, how our socio-cultural spheres, our heritage roots, context, and art and material culture, as have much informed and built a unique civilization in the past thousands of years ago, are again the resort for reviving that civilization in our present and future through the brilliant minds of our scholars, educators and students. Issues such as authenticity, innovation, and unique identity, have been at stake, when it comes to adopting technologies in the built environment, due to the accumulation of borrowed and imported models and styles of design and construction, with unfortunate superficial and stereotypical schemes of design and production. It is time for this community to be an agent of change again, to lead again, and to continue to inspire the world again. This is what this forum is about.

This venue could not have been possible without the immense dedication, support, and commitment of such an amazing and devoted group at the University of Petra. I would like to extend my sincere gratitude and appreciation, on behalf of the ASCAAD Board of Directors, to Professor Amer Al-Jokhadar and his outstanding team for their huge efforts and investment in making this event happen in such challenging times and testing conditions, always taking everything with a constant smile on their faces, despite the sleepless nights and tremendous effort they have put into the making of this venue.

I would like to extend a warm appreciation to the scientific and organizing committees from both the University of Petra and ASCAAD, who have worked tirelessly to put this conference together. This event would also not have been possible without our sponsors, our great authors who contributed amazing pieces of work, our workshop moderators, as well as a wonderful group of reviewers from all around the world, supported by our amazing network of sister CAAD organizations. I wish you all the ASCAAD community a fruitful and memorable experience coming out of this conference, and hope you all continue to lead and inspire.

Sherif Abdelmohsen
President of ASCAAD

ACKNOWLEDGMENTS

First and foremost, we thank all paper authors featured in this conference for their hard work, dedication and commitment. We are grateful to our distinguished keynote speakers *Prof. Marcos Novak*, and *Dr. Suleiman Alhadidi* for their extremely insightful talks and for their generous commitment to the conference. We would also like to thank the pre-conference workshop moderators *Nagy Elsayed, Maher Aakel, Mostafa Khaled,* and *Ahmed Osama* for the highly interesting workshop sessions they conducted prior to the conference.

We would also like to extend our thanks and gratitude to all session chairs: *Shatha Malhis, Hadeer Merza, Fatima Al-Nammari, Saba Alnusairat, Amro Yaghi, Lama Abu Hassan, Aya Musmar, Yasmine Soudi, Raid Essoh, Amar Bennadji, Huda Salman, Sema Alacam,* and *Mostafa Alani*. Many thanks to the 75 members of the international reviewing committee who have worked tirelessly to support the double-blind peer review process and the evaluation of 142 abstracts and 57 full papers. Such a demanding task in a tight timeline and working within challenging circumstances is highly appreciated.

At UOP, thanks are due to *Prof. Rami Abdel-Rahim,* the President of UOP, and *Prof. Faisal Aburub*, the Dean of Scientific Research and Graduate Studies, for their continuous encouragement and support in hosting the conference. Also, thanks are due to *Arch. Yasmine Soudi* for her support in making this conference happen, managing the registration process, and organizing all activities since December 2022, *Dr. Amro Yaghi* for his support in moderating the pre-conference workshops, and *all UOP support team*. Gratitude and thanks to conference sponsors: *University of Petra*, Jordan Engineers Association, and *Al Qabali Jewelry* for their generous contribution. All thanks to the dedicated conference committee members *Amer Al-Jokhadar, Sherif Abdelmohsen, Yasmine Soudi, Amro Yaghi, Hadeer Merza, Shatha Malhis, Fatima Al-Nammari, Amar Bennadji,* and *Huda Salman.*

Warmest regards and thanks to the unknown soldiers behind this success. Technical support team: *Bayan Radaideh, Mahmoud Rawashdeh, Batool Al Qararaa, Sarah Abu Alsoud,* and *Abdullah Qtaishat*; Graphic designer: *Hamzeh Zayed*; Financial team: *Bara'a Al-Khawaldeh, Nael Aldahleh,* and *Mazen Alqunneh*; Public relations: *Alaa Arabiyat, Rawan Taweel*, and *Sami Asmar*; Support team: *Shatha Qtait, Mirna El Dier, Mohammad Omar, Yazan Amarat,* and *Muna Ansari*; Administrative team: *Wafa' Daglus, Dana Al-Azazi,* and *Ghassan Tamari*; and *UOP student ushers*.

Amman, November 2023
Amer Al-Jokhadar
ASCAAD 2023 Conference Chair

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KEYNOTES

MARCOS NOVAK

Director, transLAB
Professor and Chair,
Media Arts and Technology Program
University of California, Santa Barbara

Keynote:
The Missions of Architecture: Architectural Computation, Culture, and Context in the Era of Generative AI

Marcos Novak is Professor and Chair of Media Arts and Technology at UCSB, and is the founding Director of the *transLAB*, a transmodal XR <*worldmaking*> lab exploring <*transformation that leads to speciation, in fact, in fiction, in action*>, affiliated with the UCSB AlloSphere research facility and CNSI (California NanoSystems Institute).

He is a transarchitect, artist, composer, and theorist who employs algorithmic techniques to design actual, virtual, and hybrid intelligent environments.

Having embraced the digital in architecture as early as the late seventies, Marcos Novak is widely recognized as a pioneer of the study of virtual and extended environments as autonomous architectural spaces, and of algorithmic, generative, and now AI and machine learning approaches to architectural design and art.

Prior to UCSB he taught at UCLA, University of Texas, Austin, and the Ohio State University, and is a frequent invited speaker and reviewer at many of the world’s most prestigious universities.

His work has been exhibited in numerous art and architecture biennials, museums, galleries, and other prominent venues around the world.

At the Banff Centre for the Arts, between 1991-1994, he created “*Dancing With the Virtual Dervish: Worlds in Progress,*” one of the first full-fledged transmodal /generative VR artworks in the world, and the first to create immersive experiences of a fourth spatial dimension (with time being a fifth dimension).

In 2000 he represented Greece at the Venice Biennale, and has participated in the Venice Biennale numerous times since, most recently in 2023.

His projects, theoretical essays, and interviews have been translated into over twenty languages and have appeared in over 70 countries, and he lectures, teaches, and exhibits worldwide. His many writings combine architecture, music, art, computation, science, and/or technology, and include such seminal papers as: *Computational Composition in Architecture* (1988), *Liquid Architectures in Cyberspace* (1991), *Transmitting Architecture: The transPhysical City* (1996), *Transmitting Architecture Revisited: On the Occasion of the UIA World Congress* (2008), and *AlloPolis: A Transvergent Manifesto* (2010), among others.

In 2008, *"Transmitting Architecture"*, the title of his seminal 1995 essay, became the theme of the *XXIII World Congress of the UIA (Union Internationale Des Architectes*, the largest architectural organization in the world.

The growing impact of his work is recognized in works such as *Architecture Unbound: A Century of the Disruptive Avant-Garde* (2021) and *The Encyclopedia of New Media Arts* (2022).

He is the originator of the *THEMAS* (technologies, humanities, engineering, mathematics, arts, sciences) model of research, pedagogy, and practice. The *THEMAS* *model* extends and enhances the STEM and STEAM approaches to include the *creative humanities* as equal participants in the holistic, integrative, and creative project of *worldmaking, in fact, in fiction, in action*. This model has been welcomed by receptive audiences around the world.

He is a Fellow of the World Technology Network, a Distinguished Affiliated Scholar of the Alexander Fleming Biomedical Sciences Research Center, and serves on the editorial boards of several peer-reviewed journals. Marcos Novak is in constant demand as a keynote speaker at conferences that span many fields.

Deeply interested in *worldmaking*, the future, and the avant-garde, he is also the fortunate recipient of a classical education in Greece, where he grew up. To reach farther into the future, we must also reach deeper into the past.

SULEIMAN ALHADIDI

Doctor of Design, Harvard University
Founder, Real-time Architecture LLC.

Keynote:
Building Tomorrow's Cities: Unleashing the Power of Smart Urban Developments and Sustainable Architecture

Dr. Suleiman Alhadidi is award-winning architect (NSW ARB Australia #9827), renowned for his groundbreaking work in adaptive, sustainable buildings, and building automation through real-time technologies. With more than 20 international awards for his architecture projects and academic achievements, he stands as a prominent figure in the field.

Having earned his doctorate degree from Harvard University, Graduate School of Design, Suleiman's research focused on developing sustainable and economical methods for maximizing building space efficiency by leveraging smart technologies, Robotics, and temporal analytics techniques. His mission is driven by a passion to create architecture that is both sustainable and adaptive, ultimately enhancing the lives of people.

Suleiman's professional journey spans across various continents, including Australia, the USA, Europe, and the Middle East, where he has contributed to the architectural landscape. His expertise has been instrumental in leading research work in collaborative robotics and performance-driven design on major projects.

In addition to his practical accomplishments, Dr. Alhadidi has been actively involved in academia. He has served as a research scientist at the MIT Media Lab, City Science Group, and has also shared his knowledge by teaching real estate advanced financing, architecture engineering, construction systems and computational design subjects at prestigious institutions like Harvard University, University of Melbourne, and the University of New South Wales.

Recognized for his leadership and expertise, Suleiman was elected to an administration position on the council of The Association for Computer-Aided Architectural Design Research in Asia. Moreover, he contributes to the field by serving as a reviewer for esteemed architecture journals and conferences, including ACADIA, CAD Futures, ASCAAD, and CAADRIA.

TECHNICAL WORKSHOPS

Workshop 1:

AI APPLICATIONS IN ARCHITECTURE (SYNTHESIS AUTOMATION OF BUILDINGS ENVELOPES)

Workshop Moderators:
Nagy Elsayed, Politecnico di Torino, Italy
Maher Aakel, Politecnico di Torino, Italy

This workshop aims to provide a new approach from early design till operation that depends on AI and genetic algorithms as it could deliver an introduction to the evolutionary algorithm's tools (Wallacei as a sample). The workshop will be a kind of active presentation to understand the technique used with open discussion, and then a brainstorming session to include this technique in relevant projects based on the experience of attendees. Objectives of the workshop are:
(A) Introduction to AI applications in architecture,
(B) Understand the Multi-Objective Evolutionary Algorithm (MOEA) as a technique and how it could be applied in architecture practice,
(C) How can we apply AI techniques to serve Building Physics (BP) and Indoor Environmental Quality (IEQ),
(D) The integration needed between computer science and architecture knowledge (what should we learn),
(E) Holistic approach to serve one coherent product.

Workshop 2:

ENHANCING CITIES' WALKABILITY USING AI AND NETWORK ANALYSIS (*SMART STEPS: REVOLUTIONIZING PEDESTRIAN ROUTING WITH ARTIFICIAL INTELLIGENCE)*

Workshop Moderators:
Mostafa Khaled, Ain Shams University, Egypt
Ahmed Osama, Ain Shams University, Egypt

This workshop explores how artificial intelligence (AI) can be leveraged to route more walkable and pedestrian-friendly pathways within the context of smart cities. Existing navigation systems usually target the shortest routes. However, users might have different preferences, such as green route, shaded route, ...etc. That's why this workshop aims to fill this gap by exploring open data and utilizing AI tools to complete the missing information to develop a more tailored navigation system that responds to user preferences.

CONTENTS

1.A.

DIGITAL HERITAGE AND CULTURE - I

FROM DIGITAL HERITAGE DOCUMENTATION TO 3D VIRTUAL RECONSTRUCTION FOR HERITAGE PROMOTION AND REINTERPRETATION

The Case of the iHeritage Project

NAIF ADEL HADDAD
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Abstract. In the last two decades, the digital age Information and Communication Technologies (ICT) development and concerns combined with rapid technology have permitted the dissemination of different digital applications (including digital documentation, virtual reality (VR), augmented reality (AR), mixed reality (MR), digital gaming, and holograms etc.) oriented toward past, present and future communication using digital three-dimensional audio-visual content. Today, we must acknowledge that 3D virtual 3D reconstruction and recreation has become an established way to build, understand, reinterpret, and promote Cultural Heritage (CH). The virtual 3D reconstruction world and multimedia industry are often considered potential marketing channels for World Heritage Sites (WHS) and heritage tourism. 3D digital/virtual reconstruction merges and embodies subjectivity in one process, playing an attractive role in heritage tourism destinations and creating image experiences, providing the first enjoyable interpretation and information for most audiences. Based on the EU-funded iHERITAGE project ICT Mediterranean platform for the UNESCO CH, this paper attempts to examine some insights into constructing the optimistic image of heritage promotion and tourism in the context of CH as it flows through both physical and virtual spaces to give a glimpse of the future of virtual reconstruction. It illustrates the development of the concepts and practice, challenges and opportunities, advantages and disadvantages, and the negative and the positive sides of the related issues of only 3D digital reconstructions, and some issues concerning the ethics based on the International Chartres and Conventions mainly in the field of scientific visualisation, such as the London Charter (2009) and Seville Principles (2011). Finally, as a practical dimension, it presents some representative examples of 3D digital/virtual reconstruction of characteristic monuments of the WHS of Nabataean Petra in Jordan for the first time.

Keywords: *scientific digital visualisation, International Charters, Nabataean Petra, iHERITAGE project, ICTs, Heritage Tourism.*

ملخص. في العقدين الماضيين، سمح تطور تكنولوجيا المعلومات والاتصالات في العصر الرقمي والمخاوف المرتبطة بالتكنولوجيا السريعة بنشر التطبيقات الرقمية المختلفة (بما في ذلك التوثيق الرقمي، والواقع الافتراضي، والواقع المعزز، والواقع المختلط، والألعاب الرقمية، والصور المجسمة وما إلى ذلك) موجهة نحو التواصل في الماضي والحاضر والمستقبل باستخدام المحتوى الرقمي السمعي والبصري ثلاثي الأبعاد. اليوم، يجب علينا أن نعترف بأن إعادة البناء والترفيه الافتراضي ثلاثي الأبعاد أصبح وسيلة راسخة لبناء وفهم وإعادة تفسير وتعزيز التراث الثقافي. غالبًا ما يُعتبر عالم إعادة الإعمار الافتراضي ثلاثي الأبعاد وصناعة الوسائط المتعددة قنوات تسويقية محتملة لمواقع التراث العالمي والسياحة التراثية. تدمج عملية إعادة البناء الرقمية/الافتراضية ثلاثية الأبعاد وتجسد الذاتية في عملية واحدة، وتلعب دورًا جذابًا في الوجهات السياحية التراثية وتخلق تجارب صورية، مما يوفر أول تفسير ومعلومات ممتعة لمعظم الجماهير. استنادًا إلى منصة البحر الأبيض المتوسط لتكنولوجيا المعلومات والاتصالات لمشروع iHERITAGE الممول من الاتحاد الأوروبي للتراث الثقافى لليونسكو، تحاول هذه الورقة دراسة بعض الأفكار حول بناء الصورة المتفائلة للترويج للتراث والسياحة في سياق التراث الثقافى، حيث تتدفق عبر المساحات المادية والافتراضية لإعطاء فكرة لمحة عن مستقبل إعادة الإعمار الافتراضي. ويوضح تطور المفاهيم والممارسات، والتحديات والفرص، والمزايا والعيوب، والجوانب السلبية والإيجابية للقضايا ذات الصلة بإعادة البناء الرقمي ثلاثي الأبعاد فقط، وبعض القضايا المتعلقة بالأخلاقيات المستندة إلى المواثيق والاتفاقيات الدولية بشكل رئيسي في مجال التصور العلمي، مثل ميثاق لندن (2009) ومبادئ إشبيلية (2011). وأخيراً، كبعد عملي، فإنه يقدم بعض الأمثلة التمثيلية لإعادة البناء الرقمي/الافتراضي ثلاثي الأبعاد للآثار المميزة للقمة العالمية للعمل الإنساني في البتراء النبطية في الأردن لأول مرة.

الكلمات المفتاحية: *التصور الرقمى العلمى، المواثيق الدولية، البتراء النبطية، مشروع التراث الرقمى، تكنولوجيا المعلومات والاتصالات، السياحة التراثية.*

1. Introduction and Scope

Cultural Heritage (CH) is the legacy of tangible and intangible attributes of a group or society. It has an intrinsic value for all people as an essential basis for cultural diversity and social development. In addition, it deals with live sites, works of communities and intangible cultural products such as literature, poetry, etc. Therefore, the long-term protection and conservation of living cultures, heritage places, collections, physical and ecological integrity and environmental context should be essential to social, economic, political, legislative, cultural and tourism development policies. Thus, CH documentation is internationally considered the first critical step for its preservation and conservation for future generations (Haddad, 2022a).

CH documentation, however, has many dimensions, such as technical, social, economic and environmental, that contribute to social and cultural well-being (Haddad et al., 2021). It includes evidence in the form of oral, written, graphic and photographic documents. Heritage information is based on documentation. It involves different layers of integrated surveying, recording, documentation, and information management activities. Generally, CH documentation includes two main actions: the gain of information regarding monuments, buildings and sites and their physical characteristics, history and problems and the process of organising, interpreting and managing that information (LeBlanc and Eppich, 2005, p. 5)].

The evolution of 3D digital technology has contributed significantly to many aspects of CH. CH is just one area of the many that are beginning to explore and realise the potential of powerful ITC technology tools. In the last two decades, CH development combined with rapid technology have permitted the dissemination of different ICTs' digital applications oriented toward past human activities using 3D content. Digital CH documentation now provides the base for conservation, reconstruction, risk assessment and mitigation, interpretation, stabilisation, identification monitoring, management, maintenance, rehabilitation, interventions, awareness and serving in educating many CH values to the public, as well as for physical *in situ* or computerised visualisation, and digital reconstruction (Haddad, 2022a). It is an integral part of any reconstruction process. 3D reconstruction images can be considered the first representative model of archaeology. Reconstruction drawings can function as a visualised theory (Hageneuer 2013; Hageneuer 2014), serving as a reference for discussing argumentation like any other scientific paper. Generally, 3D CH reconstruction can contribute in understanding the past and can be seen in films, museums and magazines to illustrate the stories behind historical or archaeological facts (Hageneuer, 2015).

The digital age of ICT rapid development has permitted the dissemination of different applications for communication using three-dimensional audio-visual content. This communication includes 3D digital documentation tools and techniques, virtual reconstruction and creation, VR, AR, MR, digital gaming, holograms etc.). According to the Principles of Seville charter (2011), virtual reconstruction is a digital process which uses "a virtual model to visually recover a building or object made by humans at a given moment in the past from available physical evidence of these buildings or objects, scientifically reasonable comparative inferences, and in general all studies carried out by archaeologists and other experts about archaeological and historical science." Meanwhile Virtual recreation "involves using a virtual model to visually recover an archaeological site at a given moment in the past, including material culture (movable and immovable heritage), environment, landscape, customs, and general cultural significance".

Three-dimensional computer graphics (3D CG) are becoming more popular because they often visualise objects more comprehensively than real ones in-situ experience and have drawn public attention, especially in CH virtual reconstruction. Digital image processing, digital orthophoto production, photogrammetry, laser scanning techniques, and 3D model processing have enabled alternative virtual products. The process of 3D CG used in 3D reconstruction and 3D modelling for reconstruction and projection mapping can be divided into three stages or categories:

- Gathering ideas and sketching: 3D image data acquisition; obtaining a 3D model of reality; 3D scanning; Photogrammetry. Manual modelling (3D Studio Max, Cinema 4D, Maya, Sketchup, etc.).
- Digitisation of historical building: data analysis and automated 3D reconstruction
- Creating the digital 3D image of historical buildings: 3D data visualisation and presentation.

Based on the EU-funded iHERITAGE project: ICT Mediterranean platform for the UNESCO CH for improving its interpretation, using new technologies and commercialising the latest research results, this paper emphasises the current role of virtual reconstruction in interpreting and understanding the history and its productions and their influential role as CH marketing channels. More specifically, it discusses the role of these virtual reconstructions in constructing the optimistic image of heritage promotion and tourism as it flows through both physical and virtual spaces to give a glimpse of the future of virtual reconstruction. It tries to demonstrate the development of the concepts and practice, challenges and opportunities, advantages and disadvantages, and the negative and the positive sides of the related issues of virtual reconstructions about the ethics based on the International Chartres and Conventions, mainly in scientific visualisation, such as the London Charter (2009) and Seville Principles (2011). Finally, it presents some representative examples of 3D digital/virtual reconstruction of characteristic monuments of the WHS of Nabataean Petra in Jordan for the first time. To summarise, the paper provides an overview of using digital heritage documentation for virtual 3D reconstruction of CH sites; meanwhile, the 3D reconstructions used from the renowned WHS of Petra as a source of information to bolster the research argument add a practical dimension.

2. Some Insights on the Link Between ICTs and 3D CH Virtual Reconstruction: Its Critical Power and Future

The link between CH and ICTs has gained increasing attention in the literature over the past few decades. Recent results permit essential insights for considering scarce resources, particularly concerning what kind of ICTs should be prioritised, especially in heritage tourism (Haddad, 2023a,18). However, understanding and combining ICT tools in virtual reconstruction and recreation can help achieve a deeper understanding and better analysis of CH. It is established that different site visitor categories have various preferences, and they show that it is vital to communicate the accessibility of ICTs (Hausmann and Schuhbauer, 2020). CH virtual reconstruction can offer the diversity of the connections between archaeology, historical sites, and the tangible and intangible aspects through digital media communication, developing the personal and collective culture through the various ICT tools. 3D digital documentation and reconstruction are fascinating subjects as many applications, such as digital gaming, VR, AR, and MR developers, revolve around settings and ideas.

In contrast to conservation theory limitations, such as measured degree of intervention, compatible material and use, physical in situ reconstruction practices have spread quickly in the past century. One of the fascinating applications of virtual worlds is the 3D reconstruction of CH. CH can be merged into virtual reconstruction in a plethora of its content. Meanwhile, virtual restoration aims to digitally preserve the information about this content digitally, enhancing its legibility. However, virtual reconstruction seeks to valorise and disseminate the object, improving its meaning and function (Pietroni and Ferdani, 2021). 3D reconstruction is just as appropriate today, considering the many armed conflicts, earthquakes and other disasters that affect CH properties and places. virtual reconstructions bring archaeology to life. Today, we can not only view reconstructions; we can experience them whether as life-sized physical models or as immersive virtual simulations, as it has become a proven tactic of building and dealing with the past as a tool for discovering new archaeological results and answer unsolved queries and even raise new ones (Hageneuer, 2015; 2020).

Any type reconstruction (physical or virtual) can have positive and negative outcomes (Haddad, 2022b). The arguments against CH physical reconstruction are mostly related to a high level of physical interventions, the use of new material, and structural reintegration techniques, affecting the monument's authenticity and the site's significant values, the ethical concern of conveying incorrect and erroneous data, prohibitive cost (Stanley-Price, 2009, Haddad, 2023b). Of the reasons for undertaking reconstruction can be a desire to restore the National identity or pride as symbolic value in the country's history as a symbol of reconciliation (Yaka Çetin et al., 2012), improve interpretation, support education and research as an essential, instructive tool for visitors, site preservation from development pressures and stabilising precarious ruined structures, continuing function or re-use or allow for a new, different process, and public awareness and Heritage Tourism promotion, thus, increasing income for the public or private authorities in charge of it. A probable weakness in the reconstruction process, observed in past projects, is represented by the possible lack of scientific reliability on the reconstructed model due to the real disjunction between the modellers producing the final computer graphics output, the archaeologist owning the knowledge for creating the appropriate reconstructive hypotheses, and the actual 3D data coming from the detailed survey (Guidi et al.,2013).

The comparative benefits of digital/virtual reconstruction can be defined based on the following issues: traditional classical archaeological reconstruction deals with specific problems which are non-existent or less severe in the digital medium. Meanwhile, working digitally accomplishes the same purpose in fewer steps. Regarding the illustration/drawing size, archaeological sketches are frequently rather significant, and it is not easy to photograph them properly. Such photographs require more processing to be printed reasonably and correspond to the described objects. In addition, future impossibility/difficulty of changes and editing. They have a limited ability to generate numerous variations of one reconstruction. Digital tools, however, permit cloning elements, separate layers of content and adjustable changes. Still, storage space in digital files can get hurt just as paper can, but a hard drive takes up considerably less space than boxes full of drawings. Moreover, backup in the cloud is an option for digital files.

Virtual CH reconstruction is an admired way of communicating the past to a broader audience. Meanwhile, it has become commonplace to understand the influence of reconstruction on memory and oblivion. It intends to inspire the viewer to experience or re-experience the CH tourism awareness and experiencing different sensations and emotions. This is primarily because of its capacity to create a desire among viewers to experience CH sites and monuments, linked with memories and stories, and that are no longer visible. These CH virtual reconstructions also encourage the public to address awareness of what these CH sites face, such as the need for conservation and protection. Meanwhile, it allows testing conceptual, constructional, and environmental features before embarking on the physical *in situ* reconstruction process. It can introduce many practical, educational, and entertaining dimensions for the public and visitors. Furthermore, it effectively engages target audiences and provides suitable materials for public engagement with the CH and their conservation (Haddad, 2022b).

3. iHERITAGE Project and 3D Virtual Reconstructions: The Case of the WHS Nabataean Petra

The EU-funded iHERITAGE: ICT Mediterranean platform for UNESCO CH (15 September 2020 - 14 October 2023) Project produces an innovation-driven growth process linking a wide range of stakeholders from six Mediterranean countries (Italy, Egypt, Spain, Jordan, Lebanon, and Portugal) by a unified approach to promoting "cross-border technological transfer, Living Labs, industry-academia collaboration, creation of spin-offs" and novel products employing the up-to-date ICT technologies, such as AR, VR, MR, for the improvement of the level of interpretation and maximisation of the commercialisation of research and supports the technology transfer by creating innovative solutions. The public can watch the historical sites and monuments as they were in the past and live each feature from their residence through smartphones and tablets (Haddad 2023a, 21-22).

Some of the project's goals are to improve CH interpretation through diverse practices and paradigms, including game-changing activities, 3D reconstructions, holography, Archéocinema and the integration of new ICT in the tourism and cultural value-adding industries, increasing employment opportunities and fostering innovation among the digital native generation who participated in the training courses, Living Labs, and support collaborations among universities, industry-academia partnerships, SMEs, start-ups, and spin-offs. The WHL sites involved in the project are seven UNESCO WHL sites in Sicily, Alhambra, Generalife and Albayzín, Granada in Spain; Memphis and its Necropolis – the Pyramid Fields from Giza to Dahshur in Egypt; and finally, the Nabataean Petra Archaeological site in Jordan, the paper case study.

This investigative section briefly shows the critical role of 3D virtual reconstruction images used among heritage accommodations in the WHS of Nabataean Petra, Jordan's major tourism attraction, with almost one million annual visitors. This site has been a tourist attraction for many years, and as an international tourist destination, it has become more attractive. However, despite the growing importance of Petra as the first tourist destination in Jordan (Haddad, 2022c; 2023a, 23), very little is known about this location's 3D virtual reconstruction image in the eyes of travellers. Recently, Dzwierzynska and Prokop (2022) described two entirely different methods for reconstructing the same structure and their comparison and evaluation. The first is from a single-photograph reconstruction method, while the other is laser scanning.

However, one must also be aware of the archaeological data and the excavated remains, simply all that has survived and that we know about. The architectural and archaeological reconstruction process is a complicated compound. At least three actions from different cultural domains must be adequately interleaved to generate a positive cross-fertilisation in the monument reconstructing process. These three pillars of reconstruction are Primary Sources, Secondary Sources, and Comparative Scientific Anticipation (Guesswork/ conjecture) based on complete and detailed documentation and analysis process—the following attempts to illustrate the reconstruction approach applied in the WHS of Nabataean Petra.

The Primary Sources: The First Step is a Good Visualisation

In some cases, a lot of the monuments survive, but generally, only the basic ground plan layout (Hageneuer, 2015)—integrating the standard set of data supplied by historical sources, on which 3D reconstructions are typically based, with the proper 3D shape visible with up-to-date passive or active 3D digital capturing methods, mainly photogrammetry and in some cases 3D laser scanning. This integration should be appropriate for providing an excellent initial theme for the reconstruction process; it is the first step that has not yet been exploited enough.

The digital visual CH documentation for reconstruction works, which starts with the process of planning how to manage the project and researching the structure's image based on the international charters and conventions and heritage principles and ethics, should be part of the virtual reconstruction as an approach process for progress, concerning the role of each one of the team: the geomatics person, architect, archaeologist, the virtual reconstruction people. Figure 1 shows briefly some photographs of the existing state of Djinn Block from Petra, No 7 and 8, with their characteristic crow steps and No 9, with the detailed formation of semi-columns and cornices from a Photorealistic 3D model at the top before the reconstruction. In contrast, at the bottom shows their 3D virtual reconstruction, based on comparative historical parallel documents from the same period and the same site of Nabataean Petra, including the proposed final colour image result.

Figure 1. Illustration showing the existing state of Djinn Block No 7, 8, and 9 from Petra at the top and their 3D virtual reconstruction at the bottom, including the proposed final colour image result.

Secondary Sources: The second step is to fill the gaps with Secondary Sources

Even when Primary Sources are utilised, we often must fill the gaps with secondary sources. These are mainly architectural parallels, as in our case, ancient depictions, descriptions, or even sometimes ethno-archaeological data. Then, it was looked at other structures to find out how they were built. It also might have needed to look at existing architecture to understand how architecture functions and what specific architectural details might indicate. Unfortunately, we had no depictions or textual evidence to help us with the reconstructed examples in Figure 2.

However, the digital visual technology for CH reconstruction was not the only possibility for the reconstruction perception in this case. The critical and debatable concern was incorporating digital virtual image technology based on digital visual CH documentation with the traditional old images from various resources, such as any available graphic and photographic material. These available old traditional documents and records are needed now more than ever if we accept that their legacy is required for this field of reconstruction. The old black-and-white photographic archives sometimes have more results than most digital data.

Figure 2. Illustration showing the existing state of Qasr El Bint in Petra at the top and its 3D virtual reconstruction at the bottom, including the proposed final colour image result.

Figure 2 shows some photographs of the existing state of Qasr El Bint in Petra with its characteristic *tetrastyle in antis*, with the detailed formation of the upper cornice and a Photorealistic 3D model at the top before the reconstruction. In contrast, at the bottom shows its 3D virtual reconstruction, based on comparative historical parallel documents of the architectural elements from the same period and the same site of Nabataean Petra, including the proposed final colour image result.

Final Guesswork/ Hypothesis decision: The third part of each reconstruction is simple Guesswork.

After developing all the primary and secondary sources, we often need to fill in some minor gaps. This third component of each reconstruction process is a hypothesis decision or simple scientific Guesswork. Of course, we need to limit it as much as possible, but there is continually some guesswork depending on the particularity of each case —no matter how much we research our structure. For example, we must make a scientific guess based on the estimated length and inclination of columns within the building. If we are lucky, we can apply several primaries and even secondary sources for that, too, but still, at the end, we need to make a subjective decision (Hageneuer, 2015). Integration of all available and published material and collaboration between the team members of scientific and professional disciplines is necessary. This collaboration might make the mission challenging.

However, this challenging mission makes it inspiring and rewarding to share and work together in this field (Haddad, 2022a, b). Figure 3 shows some photographs of the existing state of the Obelisk Tomb and Bab As-Siq Triclinium at Nabataean Petra with its characteristic four obelisks and the detailed baroque formation of the Triclinium at the top before the reconstruction. In contrast, at the bottom shows its 3D virtual reconstruction based on old traditional documents and records of the monument. It also compares historical parallel documents of the architectural elements from the same period and the same site of Nabataean Petra, including the proposed final colour image result.

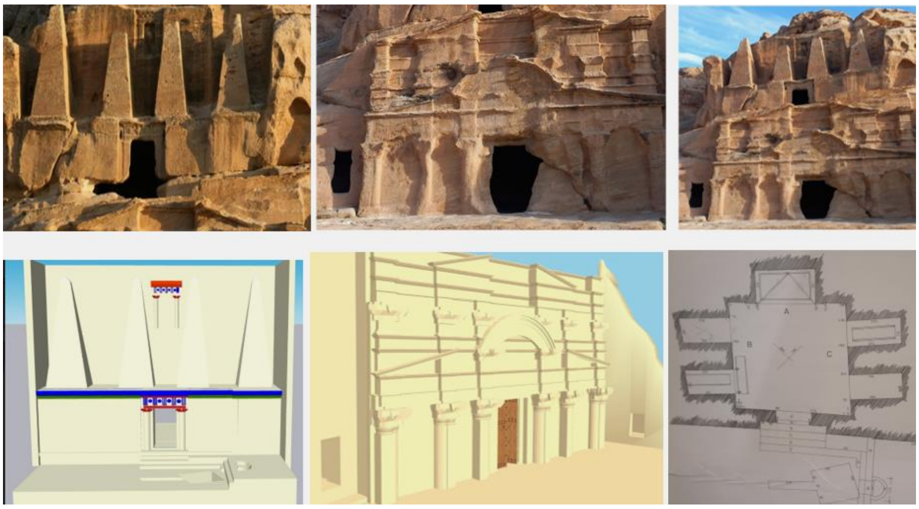

Figure 3. Illustration showing the existing Obelisk Tomb and Bab As-Siq Triclinium in Petra at the top and its 3D virtual reconstruction at the bottom, including the proposed final colour image result.

There are also a few aspects that need to be carefully taken into consideration. First, the context: an extensive reconstruction of a site or a monument on which nothing has remained intact may give an uncomfortable impression of trickery. It appears that, even if all the theoretical conditions for implementing a reconstruction project are met, one has to face a fundamental issue: What for? Is it worth it? The goal is to recognise and acknowledge the object's shape, form and function in its current broken and decayed state. Moreover, with this in mind, approximate its shape, form and function as they were when the object was new and un-damaged (Pospíšil,2012, p.3; Hageneuer, 2020).

4. Discussion and Recommendations

Over the last few years, a rapid expansion in literature and a developing body of knowledge has been demonstrated by the quantity of new research on virtual reconstruction heritage. However, meanwhile, they can be considered a powerful marketing and promotional tool and provide both long and short-term promotions for enhancing CH. On the contrary, there is an unclear critical issue of how these will affect the site's significance (e.g. it is OUV/Authenticity/Integrity and physical state). The impact on the site's importance/OUV/authenticity/ integrity/physical state can be challenging. However, a holistic discussion of the triple bottom line of socio-cultural, economic, and conservation issues regarding virtual reconstruction is still uncommon. Much work will need to be undertaken to establish if there is any impact of the likely increasing visitor numbers on the physical state of the CH site, which should include risk evaluation and assessment.

The importance of 3D digital CH documentation is evident in research, protection, conservation, stabilisation, identification, interpretation, reconstruction, management, raising awareness and helping in educating the public regarding the CH values, data recovery, and mitigating losses resulting from new construction (Haddad, 2022a). In times of crisis, documentation plays a central role. It can produce a lasting record of CH if it is lost and must be well-thought-out (Haddad, 2022b). As CH sites, with the help of 3D digital technologies such as scanning and photogrammetry, are constantly increasing, we need to establish and develop appropriate international charters about how much the digital world has a considerable influence on the broader audience (Haddad, 2023b) and how it affects the audience perceptions about identity and beliefs, then how to deal with it.

A recent study has proposed that "history-linked and heritage-based tourism, and its engagement in the never-ending telling of stories, is becoming solidly entrenched as a contribution to the popularisation and consumption of the record of history" (Fagence, 2019). Accepting that virtual heritage and archaeology now play a significant role in exploring immersive CH products that enhance our understanding of our ancestors' living environments, and can be a helpful marketing tool for tourism destinations, however, we must acknowledge that the process from seeing a virtual reconstruction to choosing a CH tourism destination alters various factors and cannot be classified as a simple cause-effect. Empirical studies are absent regarding this effect compared with the limited film tourism that has attempted to address the virtual reconstruction's influences on viewers' perceptions.

Virtual reconstruction and recreation can be used positively to draw in tourists while allowing visitors to understand better the CH site itself and its role within the country's nature. It can support scholars analyse, interpret different hypotheses to make simulations in which real and virtual together can create an evolutionary and creative process, social interaction translates into evolving knowledge. Physical in situ and virtual reconstruction should no longer be judged as opposed but as a "continuum", bringing values to the CH and human experience. They comprise the observer, who has become an active participant with a leading role (Haddad, 2022b).

However, future research must look at WHS and heritage sites in this respect to ensure their significance is accurate and adequately integrates and combined the rapid expansion in literature and research results with ICTs, with the phenomenon of Film tourism, digital gaming-changing activities, VR, AR, MR and holography in the tourism and cultural value-adding industries (Haddad, 2023a, 25). However, the impact on the site's significant OUV/authenticity/integrity/physical state can be challenging.

CH virtual reconstruction must use dynamic, accurate and realistic heritage stories, events, locations, and monuments that can be leveraged to convey messages, deliver content, enrich the user experience, and engage in activities that, if shown traditionally, can be exhausting. By applying this dynamic nature, virtual reconstruction can become a valuable tool for cultural and sustainable tourism, awareness and promotion programs to increase engagement and diversify the offer. Virtual reconstruction should be used to increase the credibility of historical reconstruction, as it has many ways to represent the past, for instance, to convey a sense of historical scene representation and send a documented accurate message in an ethical way. Furthermore, by making it very hyper-realistic, the background of archaeological and cultural remains is created in a very realistic way, allowing the viewer to dump in search of the remains of the past.

The problem is that CH virtual reconstruction sometimes creates fake history but also sends (knowingly or unknowingly) a fake message. Therefore, more attention should be given to the accuracy of historical documents, as they can affect the images and appeal to broad audiences, locally and globally. This, while some virtual reconstruction with historical contexts, qualifies as a medium to make history and can create politically dishonest discriminatory behaviours towards certain groups of people by enforcing programmed ideological views. Converting incorrect data influences individuals' political and cultural perspectives and can positively and negatively affect their political beliefs. However, including inaccurate/faulty components is crucial in maintaining CH virtual reconstruction immersive and entertaining aspects. Another critical issue is whether the context's historical and architectural reconstruction is “done according to the latest historical and archaeological assumptions and discoveries. This issue is a dilemma and will make the historical reconstruction realistic but also accurate and ethical, both architecturally, socially, and legally” (Haddad, 2023b, and a, p. 28).

From this point of view, a significant collaboration and communication between all the parties involved, from archaeologists, historians, and architects to ICT people through mainly digital channels, must be allocated within a flexible and resilient approach to enhance CH transparency promotion ethically. The makers and developers of virtual reconstructions should consider the authority to influence the public’s political and cultural perceptions of world politics and impact their political behaviour. On the one hand, these virtual reconstructions gave systematic ethical rise to social pages and websites.

On the other, the perspective of flexible and resilient copyright issues must now be established in a related International Charter and how to deal with all the involved parties. Accepting that watching a virtual reconstruction to visiting the CH site is complex, alters various factors, and cannot be classified as a simple cause-effect, from the point of view, there is a need for more novel heritage enhancement techniques to augment its interpretation, level of taking advantage of up-to-date technologies and commercialising the latest research results, in which virtual reconstruction projects to let the user live many well-renowned CH reconstructions which can have plentiful impacts on the heritage promotion image.

Considering the aspects explained above, in a world where virtual reconstruction and digital gaming productions, such as those behind Assassin's Creed, are becoming increasingly alluring, the power of attraction they can exert over people is unquestionable. As an example, according to Donald and Reed (2020), Assassin's Creed Origins marks the distinction between historical accuracy, which relates to the past as it existed in time, and historical authenticity, which relates to how the past is virtually recreated through cultural identity and its relationship with local and global communities' collective memory. There is concern about negative behaviour that can occur during exceptionally competitive multiplayer games. However, projecting a CH through these video games is an attractive and economical approach for national and international entities to expand knowledge about a country's CH aspects.

To summarise, there is a crucial need to reexamine the role of the virtual reconstruction industry in constructing the optimistic destination image of heritage tourism and experience as it flows in both physical and virtual environments. According to the requirements of our digital age, both settings, as dynamic and generate meanings, merge and embody subjectivity and objectivity now in one process. This process encourages building a critical, informative, and promotional drive. There is a need for more novel techniques to enhance its interpretation, level of taking advantage of up-to-date technologies and commercialising the latest research results, in which the iHeritage project lets the user live many well-renowned scenes of 3D virtual reconstructions which can have numerous impacts in the heritage destination image.

5. Concluding Remarks

Promoting and investing in CH based on ICTs' digital tools can break the distances between the past, present, and future. The impact of ICTs on future virtual reconstruction is evident. Virtual reconstructions have achieved significant realistic and aesthetic effects. With the ICTs' realism, achievements it is possible to attract an audience that expands the place of cultural edutainment, thereby learning through the exciting atmosphere and identifying some aspects of the cultural world that otherwise would never have been remembered. ICT tools can be brought to life in a new and engaging way CH. It permits looking at CH differently. These ICT tools can transform many CH themes from dull and dusty to fascinating. Therefore, ICTs are increasingly crucial in CH documentation, interpretation, virtual reconstructions, conservation. With an incredibly effective track for pioneering and upgrading the cultural tourism experience.

There is a need for further analysis of the impact of virtual reconstruction products on CH destination images, which have not received any attention in the literature. Considering that the first historical reconstruction challenge was capturing images that might interest people, what is required is not only to identify the benefits of the CH virtual reconstruction but to explain what makes people visit a destination that appeared in these new interpretive tools and understand how tourism promotion might occur through these virtual reconstructions. The site manager must also work more in this field to see how it can be promoted more effectively.

Finally, ICTs have an unlimited future if combined with artificial intelligence (AI) as it has become an active subject in the CH virtual reconstruction, a task that needs to be tackled quickly. ICTs' future and AI concerning virtual reconstruction and creation can shape our CH digital resources, stories, plots, storylines, and brand images. However, the dilemma might make CH virtual reconstruction and creation realistic but not consistently accurate and ethical, both architecturally, socially, and legally. Further studies should focus on what and how CH virtual reconstruction and recreation can offer and represent it in a modern key of AI within and beyond the physical dimensions of place in an ethical and transparent approach. Therefore, what is needed is to rethink historical and scientific critical rigour within an ethical transparency edutainment approach combined with virtual reconstruction according to the ethical CH key concepts of authenticity, integrity and transparency at least based on the London Charter (2009) and the Seville Principles (2011), but also even developing the versions of these two Charters. In this regard, the wish to create and empower a virtual relationship between the CH virtual reconstruction and the audience is a must, as this could be markedly useful in cases where conservation may be needed at these sites.

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تطبيق العناصر التراثية البصرية لتعزيز الهوية فى التصميم الداخلى المعاصر

حالة الدراسة: مبنى الرئاسة فى جامعة اليرموك

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ملخص: تهدف هذه الدراسة إلى تعزيز الهوية من خلال توظيف التراث الأردني والمحلي، وتأكيد أصالته والحفاظ عليه من الاندثار. وتم استخدام منهجي البحث (الكمي والنوعي) وجمع البيانات من خلال توزيع الاستبانة على طلاب التصميم الداخلي في جامعة اليرموك - إربد، حيث توصلت النتائج إلى تفاعل إيجابي مع المفاهيم المتعلقة بالتراث. تم أيضًا إجراء مقابلات مع مختصين وأكاديميين معماريين ومصممين للاستفادة من آرائهم، وأجري تصميم تطبيقي لتوظيف الأنماط التراثية في مبنى الرئاسة في جامعة اليرموك. الدراسة توصي بتعزيز توظيف التراث من خلال تقنيات الرسم والتنفيذ ثلاثي الأبعاد لتعزيز الهوية والتصميم الداخلي.

الكلمات المفتاحية: *التراث، الأصالة، الهوية، المعاصرة، التصميم الداخلي.*

Abstract. This study aims to enhance identity by employing the Jordanian and local heritage and confirming its authenticity and preserving it from extinction. The research methodology (quantitative and qualitative) was used, and data was collected by distributing a questionnaire to interior design students at Yarmouk University - Irbid, where the results reached a positive interaction with concepts related to heritage. Interviews were also conducted with specialists, academics, architects, and designers to benefit from their opinions, and an applied design was conducted to employ traditional patterns in the presidential building at Yarmouk University. The study recommends promoting the use of heritage through three-dimensional drawing and execution techniques to enhance identity and interior design.

Keywords: *heritage, originality, identity, contemporary, interior design.*

1. المقدمة

بداية، يجب التأكيد على أهمية تسجيل الحياة والخبرات منذ فجر التاريخ لتشكيل الحضارات والثقافات التي تنتقل عبر الأجيال وتمثل تراثًا يعبر عن الهوية الوطنية. وفي الأردن بشكل خاص، يوجد تنوع جغرافي فريد ينعكس إيجابياً على التراث الحضاري، سواء كان غير ملموس بما يحويه من دين وعادات وتقاليد أو ملموس بالمباني الأثرية والحرف التقليدية والأواني الفخارية.

ومن هذا المنطلق، تعتبر علاقة المصمم الداخلي ببيئته مستمرة ومهمة للحفاظ على الأصالة ومواكبة التطورات المعاصرة، والتي يمكن أن تتجلى في الابتكارات المعاصرة التي تعكس قيم وعناصر التراث.

في النهاية، يمكن للمصمم الداخلي المعاصر الاستلهام من قيم وعناصر التراث لإيجاد خصوصية تشابهت فيها الأشكال وامتزجت حتى فقدت خصوصيتها إلى حد كبير، ولكنها تعبر عن شخصية المصمم وبصمته المميزة في ضوء الأسلوب والطراز المميز، ليخرج في النهاية بإنتاج وتصميم أصيل وفريد من نوعه.

2. مشكلة البحث

يمكن صياغة المشكلة التي نواجهها في التصميم الداخلي والأثاث في الأردن بأن الحياة المعاصرة تمتاز بالانفتاح على العالم، وهذا أدى إلى زوال الحدود الثقافية بين الشعوب، وظهور مبانٍ معمارية تفتقر للهوية المحلية في التصميم الداخلي والأثاث، ولا تتناسب مع الثراء الثقافي في الأردن. وقد يؤدي ذلك إلى فقدان الوعي الثقافي الذي يتمتع به التراث الأردني، الذي يمثل صورة زاهية ومشرقة لنقاء وأصالة الأردن. ومن هنا، يجب العمل على استخدام العناصر التراثية بطريقة حديثة ومبتكرة في التصميم الداخلي، لإنتاج تصميم يواكب روح العصر ويحافظ على الأصالة والهوية الثقافية المحلية، والتي تعتبر جزءاً من تراث الأردن الغني والمتنوع.

3. أهمية البحث

تحقيق الهوية التراثية في التصميم الداخلي بمعاصرة العناصر التراثية الأردنية وإربد بشكل خاص، بالإضافة إلى تسليط الضوء على الدور المؤثر للمصمم الداخلي في تطوير العملية التصميمية ونشر ثقافة التراث الأردني عالميًا، وإضافة قيمة لبرامج التصميم الداخلي في الجامعات الأردنية والمكتبات الأكاديمية.

4. أهداف البحث

الهدف الرئيسي للدراسة **هو تحقيق الهوية من خلال توظيف العناصر التراثية الأردنية في التصميم الداخلي المعاصر. تحقيق الهدف الرئيسي يتضمن الأهداف الفرعية التالية:**

- تنمية الوعي الثقافي والحس الجمالي والتذوق الفني بهوية التراث الأردني لدى المجتمع.
- اكتشاف العناصر التراثية المحلية لتحقيق تصميم داخلي معاصر ومبتكر.
- التأكيد على الأصالة والحفاظ على التراث من الاندثار من خلال النشر الأكاديمي واستخدامه في التصميم الداخلي.

- دراسة التجارب العالمية والمحلية في المحافظة على هوية المجتمع في التصميم الداخلي والعمراني.
- إنتاج تصميم داخلي محلي يواكب العصر ويعتمد على العناصر التراثية المستمدة من التراث الحضاري والمعماري، من خلال عمل مقترح تصميمي لتطبيق العناصر التراثية في تصميم داخلي معاصر في مدينة إربد.

5. تساؤلات وفرضيات البحث

إن التساؤل الرئيسي للدراسة يتلخص في مدى الاستفادة من توظيف العناصر التراثية وانعكاساتها الفكرية والتعبيرية في تصميم الفراغ الداخلي المعاصر؟ وعليه تندرج تحته الفرضيات التالية:

- سيؤدي معرفة العناصر والقيم التراثية التي يمكن إحياؤها بتصميم يواكب روح العصر إلى المحافظة على الأصالة والهوية الحضارية.
- ستنعكس مدى الاستفادة من توظيف العناصر والقيم التراثية في أداء وكفاءة التصميم الداخلي المعاصر.
- ستؤثر معرفة الأبعاد الثقافية للعناصر التراثية على مهارات وفكر المصمم الداخلي المعاصر.

6. حدود الدراسة

الحد الزماني: تتحدد الدراسة زمانياً بدراسة التراث ومصادر التراث الأردني منذ عام 1900 – إلى عصرنا الحالي 2023م.

الحد المكاني: تتحدد الدراسة مكانياً بدراسة تراث المملكة الأردنية الهاشمية بشكل عام ودراسة تراث شمال المملكة (إربد) بشكل خاص.

الحد الموضوعي: تقتصر في دراسة العناصر والقيم التراثية وإمكانية توظيفها في التصميم الداخلي المعاصر والتي من شأنها قد تحقق وتعزز الهوية.

7. مصطلحات البحث

1.7 **التراث (Heritage):** لغوياً هو ما ورثناه عن الأجداد؛ وأصلها من ورث، وتطلق كلمة التراث على العناصر الثقافية التي تنتقل من جيل إلى آخر، كما أنه مصطلح يعني أيضاً بالإنجليزية Legacy، ظلت كلمة (التراث) محدودة الاستعمال حيث تنوب عنها كلمة (الموروث) في كثير من الأمور، وبالتالي شاع استخدامها مقابل كلمة تراث باللغة الإنجليزية بمعنى Tradition؛ أي انتقال العادات أو المعتقدات من جيل إلى آخر أي توريث القديم (التهانوي، 1996). أما اصطلاحاً هو مرجع ديناميكي ووسيلة إيجابية للنمو والتغيير، والتراث عبارة عن ذاكرة جماعية لكل منطقة محلية أو مجتمع لا يمكن استبداله، ويمثل قاعدة مهمة للتنمية والازدهار في الوقت الحالي والمستقبلي، ويجب أن يشمل على العديد من الجوانب الجماعية للمجتمع التي يمكن نقلها من جيل إلى جيل لضمان استمرارية الممارسات المجتمعية المرغوبة (Luigi Petti, 2020).

2.7 **عناصر التراث (Heritage Elements):** يقصد بها المفاهيم المرتبطة بتوظيف التراث والتي تتمثل في (الطابع، الهوية، الطراز). فيعرف الطابع: بأنه مجموعة من الضوابط البصرية والتشكيلية، التي تعكس بصدق ملامح مجتمع وثقافة جماعة إنسانية محددة. يقال طابع المدينة أي هي الخائص التي تميزها عن غيرها من المدن، وهو نفسه الذي يؤدي إلى إحساس السكان بأنهم في بيتهم أو في مكانهم الخاص، وهو الذي يؤدي إلى شعور الزائر بأنه في مدينة

ما بعينها تختلف عن غيرها (فقيه، تأصيل الطابع المعماري المكي في عمارتها الحديثة ، بحث ضمن رسالة ماجستير، 2010). أما الهوية : فهي تعبر عن العناصر المتميزة والمتكررة في طابع المكان، والتي تضفي على العمل التصميمي ملامح خاصة، تجعله متميز عن مثيله من الأعمال، كما تكسبه ميزة تجعله واضحا عن غيره (المذحجي م.، 2006). والطراز: هو مجموعة من الضوابط البصرية والتشكيلية المتميزة في التصميم، التي وإن ارتبطت أصولها بمجتمعات وثقافات وجماعات إنسانية محددة، إلا أنها بعد أن تماسكت ملامحها و تبلورت و تميزت أصبحت إلى حد كبير مجردة عن المحيط والمجتمع والثقافة التي أفرزتها، بحيث أصبح من الممكن استرجاعها واستنساخها في محتويات حضارية مغايرة تماماً عن نشأتها وأصولها كالطراز الإسلامي، والكلاسيكي (محمد م.، الموروث المعماري وأثره على العمارة المصرية المعاصرة ، رسالة ماجستير، 2016).

3.7 **التصميم الداخلي (Interior Design):** هو إحدى فروع العلوم الهندسية، الذي يربط بين الهندسة المعمارية والاحتياجات الوظيفية والجمالية في الفراغات الداخلية، والذي من خلاله تتحقق الراحة النفسية والجسدية للفرد؛ إذ يتكون من كلمتين (التصميم) وتعني الابتكار والإبداع، وكلمة (الداخلي) وتعني محددات الفراغ الداخلي (حجازي، 2012).

4.7 **الأصالة (Originality):** (إحياء التقاليد المتوارثة) وتعني العودة إلى أصولنا وجذورنا التاريخية والفكرية و الانتفاع الواعي بها وبتراثنا السابق وينبغي أن تحمل معنى التطور لمواكبة متطلبات العصر، حيث حاول العديد من الباحثين ربط مفهوم الأصالة بالإبداع، اعتماداً على أن الأصالة صفة تشمل عملية الإبداع ضمناً، فهي تمثل حجر الرحى في تكوين العقل الإبداعي، فالأصالة لا تشير إلى كمية الأفكار التي يعطيها المبدع، وإنما تعتمد على قيمة تلك الأفكار ونوعيتها، يمكننا القول إن الأصالة مبدأ لنزعة قومية تسعى إلى توضيح الهوية العربية في الفن والتصميم الداخلي الحديث من خلال تحقيق نتاج فني ينتمي إلى تراث متميز بالأسس الجمالية (عبادة ج.، 2006).

5.7 **المعاصرة(Contemporary) :** مصدر (عاصر)، وتعني معايشة الحاضر بالوجدان والسلوك والإفادة من كل منجزاته العلمية والفكرية وتسخيرها لخدمة الإنسان ورقيه (معجم الغني). بحثياً: فالتعريف مرتبط بالتصميم الداخلي المعاصر، وهو أسلوب عصري وحديث يمكن التعبير عنه بأشكال وطرق متعددة، والتي دائماً ما تتحول مع الوقت وظهور الابتكارات الحديثة، وغاية المصمم في هذه الدراسة هي إنتاج تصميم ذات بعد تراثي، من منطلق احترام القيم وإضافة كل ما هو جديد ومستخلص من روح العصر.

6.7 **الهوية (Identity):** تعرف الهوية في اللغة بأنها مصطلح مشتق من الضمير (هو)؛ ومعناها صفات الإنسان وحقيقته، وتستخدم للإشارة إلى المعالم والخصائص التي تتميز بها الشخصية الفردية. أما اصطلاحاً فالهوية (الثقافية) بمفهومها العام تعني "أنها العملية التي تميز الفرد بنفسه عن غيره، أي تحديد الشخصية ومن السمات التي تميز الأفراد بعضهم عن بعض (سليمان، 2006) " وأنها العادات والتقاليد والمكنوز الثقافي والعمراني والفنون (شعبان، 2008).

8. الدراسات السابقة

8.1 الدراسة البحثية الأولى بعنوان (أهمية دور التصميم الداخلي في تعزيز الهوية الثقافية العربية للحيز الداخلي) للباحث (هاني فران،2019)؛

حيث أكدت بأن الهوية تعد من أهم الجوانب التي تميز حضارة عن أخرى، وأن التنوع في التصميم الداخلي يلعب دوراً هاماً بالتأكيد على المضمون الفكري للمصمم الداخلي الذي يسعى في تحقيقه داخل الحيز.

8.2 الدراسة البحثية الثانية، بعنوان (استخدام العناصر التراثية في تصميم الفراغات الداخلية المعاصرة) للباحث (باسم موزان،2020)،

فهي أثبتت تحقيق مفهوم الأصالة، وبأن الأصالة والمعاصرة لا تنفصلان، ويأتي تحقيق الطابع التصميمي كنتاج لاستخدام عناصر التراث من خلال مجموعة من المؤثرات الخارجية التي تؤثر في التصميم الداخلي، وهي (المحددات البيئية والإمكانات التكنولوجية الحديثة).

8.3 الدراسة البحثية الثالثة التي جاءت بعنوان (إحياء القيم المعمارية التراثية في العمارة المحلية المعاصرة، حالة الدراسة: مدينة غزة)، للدارس (محمود صيدم،2019)،

فهي أكدت بالجمع ما بين القيم المعمارية وإمكانات العصر التقنية في عملية تصميم واحدة، والاستفادة من مضمون العمارة التراثية في أعمال العمارة المعاصرة المواكبة للزمن والحداثة؛ ولضمان استمرارية الهوية.

8.4 قدمت الدراسة البحثية الرابعة بعنوان (القيم الجمالية لمفردات التراث الأردني وتوظيفها في التصميم الداخلي بمنطقة الاستقبال للمنشآت السياحية) للباحث الدكتور (محمد إمام،2021)، رؤية تصميمية لتوظيف القيم الجمالية للتراث الأردني في التصميم الداخلي والأثاث للمنشآت السياحية، وأكدت هذه الدراسة مبدأ الاختزال والتجريد لتبسيط خطوط التصميم.

8.5 وفي الدراسة الخامسة والأخيرة، للباحث (أحمد الزعبي،2021) والتي جاءت بعنوان (إحياء العمارة في البيوت التقليدية في مدينة إربد، الأردن)، قدمت تعريف عن البيوت والمعالم التراثية في إربد، وهدفت بمحاولة إحياء وتجديد هذه البيوت والمواقع وترميمها، من أجل ترويج السياحة في الأردن، وأن دراستها وتحليلها تؤدي إلى الاستفادة من معرفة مبادئ العمارة المستدامة.

9. تعقيب على الدراسات السابقة

أكدت الدراسات السابقة في تصميم الفراغ الداخلي المعاصر على أن استخدام العناصر التراثية يساهم في تعزيز الهوية الثقافية وتحقيق الأصالة والمعاصرة معًا. وتوصلت الدراسات أيضًا على أن دمج القيم التراثية مع التصاميم المعاصرة يعزز استمرارية الهوية ويدعم التنمية الثقافية والسياحية في المنطقة.

الإطار النظري

1. المحور الأول: دراسة التراث (عالمياً):

1.1 مفهوم التراث وماهيته:

إن التراث هو تلك الحضارات السابقة التي يتوارثها الأجيال؛ فالتراث لا يمكن حصره في تعريف، حيث إنه يشمل الأشياء المادية والمعنوية والآثار، وكذلك الموارد الطبيعية وكل ما له علاقة بالإنسان (عباس، 2021).

1.2 تعريف التراث:

عرف التراث لغةً على أنه: مصدر من الفعل "ورث" وهو ما يخلفه الرجل لورثته، وكلمة "تراث" حسب المعجم الوسيط للمعاني ؛ هي "الإراث" وجذرها الثلاثي "ترث" ، فمن ترك تراثاً، ترك إرثاً ينتقل من جيل إلى آخر (الإفريقي، 2004).

وقد استخدمت الكلمة عالمياً، فهي تعني بالإنجليزية Heritage، للتدليل على الميراث الحضاري الذي تخلفه الأمم لأجيالها اللاحقتين، والميراث الحضاري أو التراث المقصود هنا: هو كل شيء صالح ينتمي إلى الماضي وينفع في فهم الحاضر والمستقبل وتطويرهما (عبادة ن.، 2021).

وخلاصة القول هو إنه رغم وضوح معنى التراث لغة واصطلاحاً، فإن الباحث لا يكاد يجد له تعريفاً واحداً فقط، فقد اختلف أهل العلم في تعريفه وتنازعوا بحسب علومه ومناهجهم، وأضحى للتراث تعريفات كثيرة تتعدد بتعدد المجالات التي تستعمل فيه. فيقال التراث الثقافي والتراث المعماري، التراث الشعبي، التراث العربي والإسلامي، ويقال التراث الحضاري أو الموارد الحضارية أو الممتلكات الثقافية الحضارية (مياطة، 2017).

1.3 أنواع التراث Heritage Types

1.3.1 التراث الثقافي Cultural Heritage:

يعرف بأنه كل ما ينتقل من عادات وتقاليد وعلوم وآداب ومختلف أنواع الفنون ونحوها من جيل إلى آخر، وهو يشمل كل الفنون الشعبية من غناء وموسيقى ومعتقدات شعبية وقصص وحكايات وأمثال تجري على ألسنة العامة (عباس، 2021، صفحة 7)، كما يشمل عادات الزواج والمناسبات المختلفة وما تتضمنه من طرق موروثة في الأداء والأشكال، ومن ألوان الرقص والألعاب والمهارات.

كما أن مفهوم التراث لا يكتمل دون أن يقترن بمفهوم الحفاظ والإحياء، فهو لا يكون تراثاً إلا إذا أحس وارثوه بضرورة التعرف إليه والكشف عنه وحمايته وإحياؤه والإفادة من قوته الكامنة التي لن تبرز إلا على قدر وعيهم بذلك التراث وحرصهم على امتلاك وتحقيق الذات من خلال تواصل الإبداع فيه وتحمل مسؤولية نقله إلى الأجيال القادمة (عبد لله، 2015).

قسم التراث إلى ثلاثة أقسام، وذلك لتحديد مفهوم وهوية التراث بشكل عام من خلالهم، وهم:

- التراث المادي:Material Heritage

ويشمل المباني الأثرية وما تم اكتشافه من آثار، وكل ما هو موجود في المتاحف والوثائق، وكذلك الثروات الطبيعية، ومنها:

الآثار الثابتة: مثل بقايا المدن التاريخية والعمائر الدينية والمعالم المعمارية والتحصينات العسكرية والمنشآت المائية والزراعية بالإضافة إلى المدافن وما نحوها.

الآثار المنقولة: وتشمل:

- المنحوتات والمواد المنقوشة والمخطوطات والمسكوكات والأدوات الفخارية والخزفية والزجاجية والمنسوجات وأدوات الزينة.
- الموروثات الحرفية والصناعية والمعمارية، مثل المنسوجات الحرفية الأصلية التي توقف إنتاجها بالطرق التقليدية التي توارثتها الناس لكونها شواهد تراث مميز يعكس الهوية المحلية، وحل محله إنتاج آلي أو استهلاكي محاكيه في الصنعة وتخالفه في الجودة والقيمة الفنية والجهد البشري (الزهراني، 2015).

- التراث الفكري Intellectual Heritage:

وهو ما تركه العلماء السابقون والكتاب والمفكرين من فكر مبادئ وثقافة، ويشمل ثلاثة أصناف:

- ما ورث عن السلف من العلوم والمعارف الدينية.
- العلوم والمعارف الطبيعية كعلوم الأوائل والتراث العلمي الإسلامي في مجالات العلوم الطبيعية المختلفة.
- الفنون الأدبية والفنون الزخرفية والخطبة ونحوها.

- التراث الاجتماعي Social Heritage:

وهو تلك المنظومة الاجتماعية وما تشمله من عادات وتقاليد وقيم تنظم الحياة الاجتماعية وهي الموروث الأهم للبشر، ويشمل:

- الموروثات الشفهية كالحكايات والأمثال والأزجال واللهجات.
- العادات والسجايا والأزياء الشعبية وغيرها من التقاليد الاجتماعية.

4.4 تأكيد الهوية وجدلية العلاقة في التصميم الداخلي:

يجمع التصميم المعاصر ما بين الأصالة والتطور، حيث يمكن أن يتمثل التراث في أسس تصميمية تستوحى منها العمارة المعاصرة، يعتبر مفهوم "ما بعد الحداثة" من أهم الاتجاهات التصميمية الحديثة التي تتفاعل مع التراث كما يتمثل هذا التفاعل في دمج العناصر التراثية بشكل مباشر أو تجريدية في إطار معاصر ويمكن تصنيف الاتجاهات الفكرية لعمارة ما بعد الحداثة إلى جزئين: تاريخي ومحلي. بالتالي، يتحقق التوازن بين التراث والمعاصرة في التصميم المعماري الحديث من خلال تأكيد الهوية التراثية في التصميم الداخلي يعد هدفًا إنسانيًا في عصر العولمة، حيث يسعى المصمم الداخلي للتعبير عن الأبعاد التاريخية والثقافية التراثية لتحقيق التفرد والإبداع، بالتوازي مع الانفتاح على الأفكار التصميمية العالمية، إذ يجتمع التصميم المعاصر مع التراث لتجسيد الطموح في التوثيق ما بين الماضي والمستقبل، وهنا يتمثل دور المصمم في تطوير مصفوفة تربط الأبعاد الثقافية والهوية بمستويات الجمال لتحقيق تصميم مميز يجمع بين الهوية والتقدم في عصر التكنولوجيا (العزيز، 2018). وخير مثال على ذلك، نموذج ومشروع المجلس الوطني الاتحادي الجديد في الإمارات FNC Parliament Complex، في الشكل (1)، الذي يوضح تأثير الهوية والأبعاد الثقافية عليها

الرسم (1) (أ+ب) : التصميم المعماري لمبنى مجلس الوطني الاتحادي الجديد، أبوظبي. المصدر :
https://www.eyrc.com/work/federal-national-councils-parliament-building-complex

التصميم الفائز بالجائزة الأولى في مسابقة التصميم المعماري للمجلس الوطني الاتحادي بالإمارات يجسد هوية متوازنة تجمع بين التراث الإسلامي والحداثة المعاصرة، ويتميز بقبة مدهشة تشبه "زهرة الصحراء"، معبرًا عن هوية متطورة للمجتمع ورؤيته للمستقبل. المكتب الأمريكي "معماريوا أيريليك Ehrlich" هو المصمم الرئيسي للمشروع.

4.1 الأسس والعناصر التصميمية التراثية في تكوين الشكل والفراغ المعاصر:

4.4.1 الوحدة Unity:
وهي اتباع أسلوب معين لتنسيق العناصر وترابطها مع بعضها البعض، وإعطائها طابعاً موحداً ليكون التصميم أو العمل جسماً واحداً (خنفر، 1998)وتتضح الوحدة في الفنون الشرقية من خلال:

وتعد الوحدة في التصميم من أهم الأسس الذي يرتكز عليها الفكر التصميمي المعاصر، وتتحقق في التصاميم الداخلية من خلال اندماج وانسجام جميع العناصر الداخلية في الفراغ كمنظومة واحدة ليخرج التصميم في شكل موحد متكامل داخليًا وخارجيًا، ووحدة الكل من هذا الجانب تتطلب **تنوع** في الأجزاء؛ لأن الوحدة دون تنوع تؤدي إلى الرتابة في التصميم، وعلى العكس فإن التنوع دون الوحدة يؤدي إلى الفوضى (كامل، 2017).

4.4.2 الإيقاع Rhythm:
وهو من أهم وسائل التعبير عن النفس (قاسم، 2002)، ويعتبر الإيقاع من الصفات الكامنة في الفنون الشرقية والمحددة لسمات التصاميم الداخلية، وهو مفردة تقع ضمن مفهوم أشمل يطلق عليه مصطلح (التنغيم)، والذي اعتبر أحد قيم الفنون الإسلامية حيث يتضح عبر المستويات التشكيلية المختلفة، وينشأ الإيقاع في التصميم الداخلي من خلال حركة العناصر المكونة للفراغ الداخلي،

4.4.3 التوازن Balance:

هو من أهم مبادئ تصميم الأثاث، حيث يلعب دورًا مهمًا في تقييم العمل الفني، ويحقق نوعًا من القبول النفسي عند رؤيته، فهو الإحساس بوجود الإنسان في وضع معتدل قائم رأسيًا ومتوازن على أرض أفقية (الرزاق، 2004). ويعد الاتزان والاستقرار من أهم الأسس التي اتُبعت في الفنون الإسلامية، حيث نستطيع أن نراه في العمارة الإسلامية في القباب وفي التكوينات الزخرفية، ويتحقق الاتزان من خلال استقرار التكوين حول محور ثابت في منتصفه، فهو يهتم بالتعادل البصري لعناصر التكوين. ويعد التوازن من أهم الأسس التصميمية المعاصرة، فالتصميمات المتزنة تبدوا مستقرة ومريحة للعين، حيث يعمل الاتزان في التصميم الداخلي على ترتيب العناصر داخل الفراغ ليعطي الإحساس بالراحة (الكريم، 2013)، ويقسم التوازن إلى (ثلاثة) أنواع:

4.4.4 التكرار Repetition :
يمثل التكرار إحدى أشكال الحركة اللانهائية، وهي صيغة لتحقيق الوحدة والنظام في العمل التصميمي، فالنقطة تمثل بداية أي عمل تصميمي وبتكرارها واستمراريتها ينتج العديد من الأشكال الهندسية والأشكال الحرة الانسيابية المتتابعة والمتراكمة، ويمكن أن نلاحظ استمرارية الخطوط والمساحات والربط بين المستويات الرأسية والأفقية في العديد من التصاميم الداخلية المعاصرة (شاكر، 1995)،

1.5 المفاهيم المرتبطة بتوظيف التراث:

1.5.1 الطابع: Character وهو مجموعة من الضوابط البصرية، التي تعكس بصدق ملامح مجتمع وثقافة جماعة إنسانية محددة، يقال طابع المدينة أي هي الخصائص التي تميزها عن غيرها من المدن، وهو نفسه الذي يؤدي إلى إحساس السكان بأنهم في بيتهم أو مكانهم الخاص، وهو الذي يؤدي إلى شعور الزائر بأنه في مدينة ما بعينها تختلف عن غيره. يتحدد الطابع التصميمي الداخلي والمعماري لأي مبنى بالملامح الآتية:

أ- مواد البناء (الخامات) والملمس Materials & Texture: العمارة التراثية تتميز بتحقيق القيم الجمالية عبر استخدام مواد البناء من الطبيعة والمحيط المحلي، مثل الحجر والطوب، مع التنوع البُعدي والجمالي، ما يعزز الانتماء للمكان والثقافة ويزيد ارتباط المبنى بمحيطه.

ب- الإضاءة واللون Lighting & Color: إن الإضاءة واللون يلعبان دورًا مهمًا في تحقيق الجمال للعمارة التراثية، حيث يؤثر تغيير شدة ونوع الإضاءة في قيمة اللون، وتأثيراتها البصرية والفسيولوجية تؤثر على مزاج المتلقي.

ت- وحدات الأثاث The Furniture: يعتبر الأثاث في العمارة التراثية ذو قيمة جمالية ووظيفية، حيث يتميز بالراحة والمنفعة، ويصمم بأناقة، مستخدمًا الخشب والأقمشة والزجاج والمعادن وغيرها من المواد.

1.5.2 الطراز Style: فيمثل انعكاس مقومات شخصية المصمم على إنتاجه، وقد يتأثر بالعوامل النفسية والاجتماعية والثقافية والجمالية

الجدول (1): نماذج عالمية في توظيف التراث في العمارة والتصميم الداخلي

متحف اللوفر في أبو ظبي	**صالة بلازا بريميوم Plaza Premium في مطار ليوناردو دا فينشي فيوميتشينو Leonardo da Vinci-Fiumicino Airport، روما**
يبين الشكل متحف اللوفر في أبو ظبي، من الخارج والداخل، حيث تتغلغل الضوء عبر فتحات القبة داخل قاعات العرض المستلهم من مبدأ المشربيات الإسلامية (حسن د.، 2022). 	صالة Rome Fiumicino في مطار Leonardo da Vinci-Fiumicino، مع تصميم داخلي مستوحى من العناصر الرومانية القديمة (Ashoura, 2021). 

2. المحور الثاني: تراث الأردن (محلياً):

- **<u>الموقع الجغرافي للأردن:</u>** تقع الأردن في جنوب غرب آسيا، شمال غرب المملكة العربية السعودية وجنوب سوريا، بين ْ خطي طول 59ْ إلى 31 وبين دائرتي عرض شرقًا 52 ْ 34 إلى 15 ْ 39 شمالًا، ولا يمتلك الأردن سواحل أو منفذًا بحريًا سوى في مدينة العقبة الواقعة في أقصى جنوب المملكة، حيث يمتد ساحل العقبة على مسافة 26 كيلومتر على خليج العقبة المتصل في البحر الأحمر(مروان، 2022).
- **<u>تاريخيًا:</u>** تاريخ الأردن يمتد من العصر البرونزي إلى العصر الحديدي. ذُكرت مناطق أردنية في الكتابات الدينية منذ 597 قبل الميلاد. أثر الإسكندر الأكبر في تنمية المنطقة وإنشاء مراكز تجارية. وحكمت اليونان المنطقة بين القرنين الثاني والرابع قبل الميلاد، بناءً لمدن مثل فيلادلفيا وجدارا. ومن ثم دخل الحكم الإسلامي الأردن بعد عام661 م، تلاها الحكم العثماني حتى 1918م، واستقل الأردن في 1946م (Stimage, 2018).
- **<u>ثقافيًا:</u>** التراث الأردني متنوع ويعبر عن هوية المجتمع بتراثه الشعبي والعمارة التراثية الريفية واللهجة. يشمل الأطعمة واللباس والغناء والرقص والعادات والتقاليد. وإن التنوع الجغرافي لأقاليم ومحافظات الأردن

انعكس إيجابياً على تراثه الحضاري، وهذا التنوع صاحبه تكامل في عناصره التراثية. إذ ينقسم التراث الأردني إلى:

أ- **التراث الأردني المادي** ومن عناصره؛ الأزياء الشعبية التراثية للرجال والنساء، ويشمل أيضاً الأدوات التراثية والمعالم الأثرية التي تدل على تراث الأردن الشعبي الأصيل، ومنها المهباش لطحن حبوب القهوة، ودله القهوة والبساط الأردني بألوانه الحمراء وغيرها، بالإضافة إلى البيت الأردني مثل بيت الشعر.

الرسم (2): تمثل الأشكال(أ،ب،ج): عناصر التراث الأردني المادي.المصدر: [/https://www.alaraby.co.uk](https://www.alaraby.co.uk/)

ب- **من عناصر التراث الأردني غير المادي**؛ العادات والتقاليد الشعبية، كالأطعمة المشهورة مثل المنسف، والطقوس المختلفة كالأتراح والأفراح الاجتماعية المختلفة مع الأغاني والموسيقى الشعبية والقصص الشعبية والشعر والنثر والأدب، والدين بأركانه وأماكنه المقدسة والشعر والنثر والأدب، الأهازيج، والدين بأركانه وأماكنه المقدسة.

الرسم (3): تمثل الأشكال(أ،ب): عناصر التراث الأردني غير المادي.المصدر: https://ich.gov.jo/node/50768

3- المحور الثالث: تراث محافظة إربد

وقع اختيار الباحثة لمحافظة إربد، حاضرة الشمال في المملكة الأردنية الهاشمية كي تكون الدراسة عليها، والتي سيتم من خلال الدراسة التعرف على تراث المحافظة، الحضارات التي مرت عليها المنطقة، والمواقع الأثرية الموجودة فيها، ويعود سبب اختيار الدراسة إلى أن:

أ- إربد هي المدينة التي تحتضن عينة الدراسة ألا وهي جامعة اليرموك (مبنى الرئاسة)، وكونها الأقرب إلى الباحثة والمجال الأوسع لها.
ب- ندرة الدراسات المتعلقة بالمحافظة وتراث المحافظة، وعدم اهتمام المؤسسات المعنية بتطويرها كما يجب.
ت- تصدر إربد حديثاً بأنها العاصمة الثقافية العربية من قبل اليونيسكو عام 2022 م (وزارة الثقافة، 2022).
ث- تحتضن إربد العديد من المدن العريقة المشهورة في التاريخ، كمدينة أم قيس، بيت رأس، طبقة فحل ... إلخ.

اهتمت الدولة الأردنية في السياحة والآثار، وهذا أمر أدى لتأسيس المتاحف وعمل الحفريات الأثرية ووضع المكتشفات في خزائن العرض بالمتاحف من القطع الفخارية والزجاجية التي تعود لعصور مختلفة، والمتحف الرئيسي وضع في دار السرايا العثمانية في مدينة إربد، لاستعمالها متحفًا وطنيًا أثريًا شاملاً يضم فيه آثار **الحضارات العديدة التي تعاقبت في المحافظة**، والمتاحف والبيوت القديمة في محافظة إربد موضحة في الجدول (2):

جدول (2) : أهم المواقع السياحية والأثرية في إربد.المصدر: تصميم الباحثة.

الاسم	الصورة	الوصف العام
متحف دار السرايا	 	تقع دار السرايا **في الطرف الجنوبي الشرقي من تل إربد الأثري**، مقابل مبنى بلدية إربد من الجهة الشمالية، ويعد من أكبر المباني التراثية في المدينة، وكان مقر الحاكمية العثمانية عندما استحدث قضاء عجلون عام 1851 م، وترجح دائرة الآثار في مدينة إربد أن دار السرايا بنيت بعد عام 1851م، حيث يلاحظ أن المبنى ليس له طراز معماري محدد ولا يرجع إلى فترة بناء واحدة وذلك من خلال الاختلاف في الواجهات المعمارية والتكوين الداخلي للفراغات، ومن حيث استخدام تقنيات وعناصر معمارية ومواد البناء وسماكات الجدران والمبنى، وفي عام 1921م اتخذت هذه الدار مقراً لإقامة قوات الدرك، ثم حولت في العقد السادس سجناً مركزياً لمنطقة إربد، ومن ثم تم تحويلها في العقد الأخير من القرن الماضي إلى متحف تابع لدائرة الآثار العامة (الصويركي، إربد المدينة، تاريخ وحضارة وآثار، الطبعة الأولى، ص59، 2006)، وبعد أن استكملت دائرة الآثار العامة أعمال الاستملاك لدار السرايا في عام 1994م، قام كادر هندسي من دائرة الآثار العامة بعمل الدراسة الهندسية والفنية للمبنى لغايات ترميمه وتم تجهيزه ليصبح مكتبة لآثار إربد في الطابق العلوي، **ومتحفاً للآثار** في الطابق الأرضي.
بيت النابلسي	 	**يعود بنائه إلى العشرينيات من القرن الماضي، بحدود عام 1925م، ويقع على الجانب الغربي من تل إربد وبجوار** دار الجودة من الجهة الجنوبية، ويقوم البناء على قطعة أرض بمساحة 228م2، صمم البناء على **الطراز المعماري الشامي (طابق أرضي وأول مع فناء مفتوح في الوسط)** وتعود ملكيته لعائلة النابلسي التي وفدت من الشام واستقرت في إربد، وقد قامت البلدية باستملاك هذا البناء بغرض المحافظة عليه وترميمه كإحدى المعالم المعمارية والتراثية المميزة في مدينة إربد، وقامت **وزارة السياحة والآثار** بترميم هذا المبنى ضمن مشروع تطوير ساحة فوعرا وتم تسليمة إلى بلدية إربد عام 2008م، ويتكون البناء من طابقين كلاهما كان مستعملاً لأغراض السكن وهما الآن مصنفان من الأبنية التراثية في إربد **التابعة لبلدية إربد الكبرى (الرجوب، 2011)**.
بيت عرار		يقع المتحف في الجهة الجنوبية الشرقية من تل إربد، ويبعد عن دار السرايا حوالي 70 م، بني البيت وفق شكل مربع، ذو حيز داخلي مغلق، وشيدت جدرانه الخارجية والداخلية بواسطة مداميك من الحجارة الجيرية، التي يكثر وجودها في عدة مناطق في إربد، ويتناوب معها في أعلى بعض الواجهات مداميك من الحجارة البازلتية السوداء، التي تشتهر بها منطقة شرق حوران، وذلك أضفى على عمارة البيت لمسة فنية رائعة الجمال (Ahmad Alzoubi, 2022). يتم الدخول إلى البيت من خلال مدخل رئيسي يعلوه عقد مدبب فتح في وسط الجدار الجنوبي، الذي يؤدي مباشرة إلى فناء داخلي واسع ومكشوف مستطيل الشكل، تطل عليه ثلاثة حجرات سكنية صغيرة الحجم، ومما يجدر ملاحظته هنا أن هذه المجموعة المعمارية وترتيبها الداخلي، قد شيدت وفق النظام المعماري المعروف بالطراز الحيري؛ وهو طراز معماري اشتهرت به العمارة العربية في الفترة السابقة للإسلام والفترات الإسلامية، الذي يتألف من إيوان واسع مرتفع يقوم على جانبيه حجرتان ويتقدمهم في أغلب الأحيان رواق يفتح على الفناء المكشوف، أطلق عليه المؤرخ المسعودي اسم الحيري نسبة إلى مدينة الحيرة (المسعودي، 1965).

بيت الشرايري	 	**يقع بيت الشرايري في الجهة الجنوبية الغربية من تل إربد،** شيد عام 1908 م على يد اللواء علي خلقي الشرايري والذي يعتبر أحد أهم الشخصيات التاريخية في مدينة إربد في أواخر الربع الأول من القرن الماضي، والذي ترأس حكومة إربد بعد تأسيسها عام 1920 م (الصويركي، الإدارة المحلية في إربد وتطورها ، 2008). وقد زار البيت الملك المؤسس عبدالله الأول والقائد عز الدين القسام وغيرهم من أحرار العرب، وبقيت أسرة اللواء الشرايري من أبنائه وأحفاده تسكن البيت حتى عام 1985 م، ومن ثم قامت بلدية إربد في عام 2005 م باستملاك البيت بالتعاون مع وزارة السياحة والآثار أعمال التأهيل والصيانة للبيت، والذي تحول بعد ذلك إلى متحف سياسي. يتألف البيت من **طابقين، اشتمل كل واحد منهما على خمسة حجرات متوسطة الحجم، وزعت بالتساوي على الجهتين الشمالية والشرقية لفناء داخلي واسع مستطيل الشكل، تطل عليها حجرات البيت السكنية** ومرافقه، ويمكن دخول البيت عبر مدخل رئيسي فتح في وسط الواجهة الجنوبية، وتمتاز عمارة البيت بواجهاته الخارجية التي فتحت بها النوافذ **المؤطرة بالعقود المتنوعة.**
متحف التراث الأردني ، جامعة اليرموك	 	**يقع متحف التراث الأردني في كلية الآثار والأنثروبولوجيا في جامعة اليرموك،** يوضح هذا المتحف من خلال **القطع الأثرية قصة الإنسان وثقافته المادية وعلاقته بالبيئة الاجتماعية والجغرافية المحيطة.** تم افتتاحه عام 1988م بالتعاون مع الحكومة الألمانية، يسرد المتحف قصة وتاريخ البشرية في الأردن عبر مراحل التطور الرئيسية بطريقة منهجية تخدم التخصصات الأكاديمية في الكلية، وتتناسب واحتياجات كل من الزوار العاديين والمتخصصين في نفس الوقت (اليرموك، 2016).ينقسم المتحف الأردني إلى عدة طوابق؛ **الطابق الأول** يحوي المنزل الريفي والصالة الرئيسية للمتحف التي تتكون من أربعة قاعات، حيث القاعة الأولى تتناول قسم ما قبل التاريخ في الأردن ويتضمن معروضات عن الصيادين وجامعي الثمار والتطور الزراعي والمجتمعات الزراعية القروية. **أما القاعة الثانية تصور تاريخ الأردن المبكر من خلال معروضات تمثل ظهور دول المدن** والدول الإقليمية والرعاة والبدو الأوائل، القاعة الثالثة تعرض الأردن خلال الفترة الكلاسيكية وتركز بشكل خاص على السكان المحليين خلال العصور البيزنطية والنبطية والرومانية، أما القاعة الرابعة والأخيرة فهي تسلط الضوء على الأردن كجزء من العالم الإسلامي وتتضمن إعادة بناء بعض الحرف التقليدية. يحتوي الطابق الثاني على مواضيع خاصة تتعلق بالتكنولوجيا والحياة الريفية والفلكلور، تمت إضافة معرض جديد لعلم دراسة العملات والمسكوكات إلى المتحف عام 2002 م (Mika, 2004).
الخلاصة		تتشابه محددات الفراغ الداخلي في معظم البيوت التراثية والمتاحف الأثرية في إربد بـ: • **شكل الأسقف المقوسة** والمستوية عالية الارتفاع ومنها ما هو مدعوم بعوارض خشبية. • **الأرضيات الإسمنتية** المكسوة بالحجر البازلتي الأسود أو الحجر الجيري الأبيض. • **الجدران المكسوة** بالطوب الطيني والحجر الأبيض والأسود ذو السماكة الكبيرة . • **شكل الشبابيك المقوسة** أو مستطيلة الشكل ذات السماكات الكبيرة والخصائص المميزة. • **الحوش(الحديقة الداخلية)** مراعاة للخصوصية والسماح بدخول الإضاءة الطبيعية. • **تضم معظم المتاحف مجموعة من القطع الأثرية** المستكشفة والمسكوكات اليدوية بالإضافة إلى أدوات من التراث الأردني والأزياء الشعبية.

3.1 جامعة اليرموك (حالة الدراسة)

تعتبر جامعة اليرموك جامعة أردنية حكومية مستقلة تقع في مدينة إربد. تأسست عام 1976م بأمر من الملك حسين بن طلال -رحمه الله-، ومنذ ذلك الحين شهدت توسعًا وتطورًا ملحوظًا. تهتم الجامعة بالنهج الابتكاري وتنمية الموارد البشرية، وتحرص على التميز في التدريس والبحث العلمي في مختلف المجالات. يتم استضافة العديد من المراكز البحثية والوظيفية من قبل الجامعة، وتعتبر جامعة اليرموك من أفضل الجامعات في الأردن والشرق الأوسط والعالم. **تم اختيار مبنى الرئاسة في الجامعة كحالة دراسية في هذا البحث بسبب كونه بحاجة لإعادة تصميم فراغاته الداخلية بأسلوب جديد ومعاصر، وكونه يستقطب الزوار من مختلف المجالات، لذلك يهدف التصميم إلى استلهام جزء من التراث الأردني بأسلوب معاصر وتحويل المبنى إلى نموذج يحتذى به في إحياء التراث في التصميم الداخلي، وبالتالي يمكن تحقيق ما يلي:**

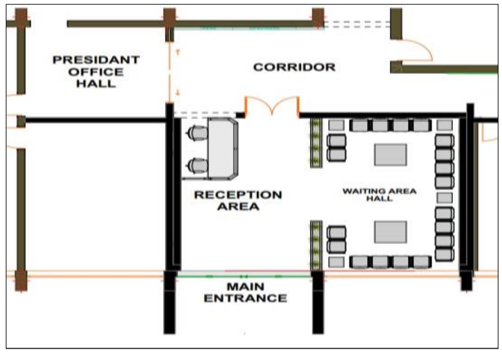
- **التميز والهوية الثقافية :**توظيف عناصر التراث الأردني يساهم في تمييز المبنى ومنحه هوية ثقافية فريدة. يمكن أن يجعل الزوار والمستخدمين يشعرون بالانتماء إلى الثقافة والتاريخ المحلي.
- **الحفاظ على التراث** :توظيف العناصر التراثية يعزز من الوعي بالتراث الثقافي ويسهم في الحفاظ عليه. إذا تم استخدام العناصر التراثية بشكل ملموس في التصميم الداخلي، فإنها تحفز على الحفاظ على هذا التراث.
- **إثراء التجربة البصرية** :يمكن أن تجعل العناصر التراثية المستخدمة بشكل جيد التجربة البصرية للمبنى أكثر إثراءً وتعميقًا. يمكن أن تكون الزخارف التقليدية والألوان التراثية والتفاصيل الثقافية جزءًا من الجمالية العامة للمكان.
- **جذب الزوار والاهتمام :**يمكن أن يجذب التصميم الداخلي الذي يحتوي على عناصر تراثية الزوار والمهتمين بالثقافة والتراث إلى المبنى. قد يكون لديهم رغبة في استكشاف وتجربة المكان بشكل أعمق.

الإطار التطبيقي

بعد الانتهاء من المرحلة الأولى من نهج الدراسة ألا وهي المقابلات الشخصية مع الجمهور المكون من المتخصصين في العمارة والتصميم، والاستفادة من آرائهم ومقترحاتهم التي تخدم أهداف الدراسة، سيتم في هذا الإطار إيجاد رؤية تصميمية لإمكانية توظيف وإحياء جزء من المفردات المعبرة عن الهوية التراثية للأردن وبالأخص تراث منطقة إربد في التصميم الداخلي والأثاث من خلال التطبيق بمنطقة الاستقبال في الطابق الأول من الرئاسة في جامعة اليرموك في مدينة إربد؛ وذلك لتنمية الوعي الثقافي والذوق والحس الجمالي بهوية التراث الأردني لزوار المكان والموظفين والطلبة.

- **عناصر المشروع والعملية التصميمية:**

بعد الزيارة الميدانية من قبل الباحثة لمنطقة المشروع وهي **(منطقة الاستقبال والاستعلامات وما حولها في الطابق الرئيسي من مبنى الرئاسة في جامعة اليرموك)**، والتقاط الصور التوضيحية لتحديد الفراغات المراد صياغة التصميم فيها، بشكل يواءم مع المحددات السابق ذكرها في الدراسة. والصور التالية توضح الفراغات التي تم تحديدها مع المسقط الأفقي، لعمل التصميم المقترح:



الرسم (4): يمثل المخطط السابق للطابق الرئيسي لمبنى الرئاسة في جامعة اليرموك.المصدر: دائرة الأشغال العامة في جامعة اليرموك.

الرسم (5)،(أ): يمثل مدخل منطقة الاستقبال في الطابق الأول من مبنى الرئاسة في جامعة اليرموك.(ب): منطقة الاستقبال من الداخل . المصدر:تصوير الباحثة.

الرسم (6): (أ+ب): منطقة الانتظار وكاونتر الاستقبال في الطابق الأول من مبنى رئاسة جامعة اليرموك.المصدر:الباحثة.

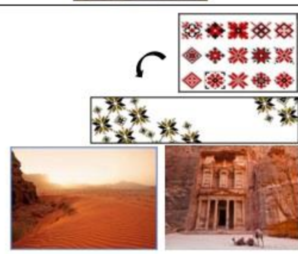
الرسم (7) :(أ+ب):منطقة الموزع الداخلي (الكوريدور) بين مكتب الرئيس والمكاتب الأخرى.المصدر:الباحثة.

الرسم (8): (أ+ب): يمثلان منطقة الكوريدور(الموزع الداخلي) المؤدي لمكاتب الموظفين .المصدر:الباحثة.

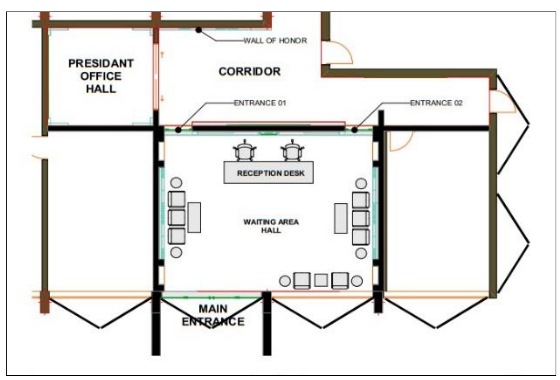
- **الفكرة التصميمية المستلهمة :**

لتحقيق أهداف الدراسة وتطبيق نتائجها، تم اختيار (منطقة الاستقبال) لإمكانية تطبيق العناصر التراثية الأردنية وأهم مؤثراتها في التصميم الداخلي والأثاث، حيث تمثل الفكرة الرئيسية الموروث التراثي الذي يجمع بين الطابع الأردني بشكل عام وطابع منطقة إربد بشكل خاص، حيث تم استلهام خطوط التصميم من التراث المعماري (طراز البيوت الأثرية) ومن الزي الأردني الأصيل وبعض المشغولات اليدوية التراثية ذات الألوان الصريحة والمستوحاة من البيئة المحيطة، وذلك من خلال تحليل تلك العناصر وتجريدها والتشكيل في خطوط التصميم لإخراج تصميم ابتكاري وجديد مستلهم من التراث بأسلوب غير مباشر(يواكب العصر). الجدول (3) يوضح عناصر التصميم الداخلي والعينات التراثية الأساسية في منطقة الاستقبال بسمة تراثية أردنية.

الجدول (3): عناصر التصميم الداخلي والعينات التراثية الأساسية في منطقة الاستقبال بسمة أردنية. مصدر الصور :
https://ich.gov.jo/node/69660 ، https://3dsky.org/

العنصر	فلسفة التصميم	العينة التراثية
الأثاث	**المقاعد :** تم تصميم مقاعد منطقة جلسات الاستقبال من القماش التراثي المستلهم من رموز ودلالات الثوب والبسط الأردني ذات الألوات الصريحة والمستوحاه من البيئة المحيطة وبيت الشعر الأردني و(الستانلس ستيل) المطلي باللون النحاسي، وذلك من خلال التحليل والتجريد في المفردات التراثية وتجريدها ولتشكيل في خطوط التصميم لإخراج تصميم جديد ومعاصر مستلهم من العناصر التراثية.	
	الطاولات (المنضدة): تم تصميم الطاولات من خشب السويد، وقد تم تشكيل القاعدة من تحليل خطوط شكل المهباش الشعبي (أداة طحن البن قديماً) بأسلوب عصري وغير مباشر.	
	كاونتر الاستعلامات: تم تصميم كاونتر الاستعلامات من الخشب الرقائقي اللاصق (اللامينيت) ، مطبوعاً عليه أشكال تم تحليل خطوطها من شكل الزخارف والرموز الموجودة في الزي الأردني الشعبي ، ولكن بأسوب وبألوان عصرية وغير مباشرة. وتم تحليل الألوان مزيج من اللون الوردي واللون البني وهي مستلهمة من ألوان البتراء النبطية وألوان صحراء الأردن.	

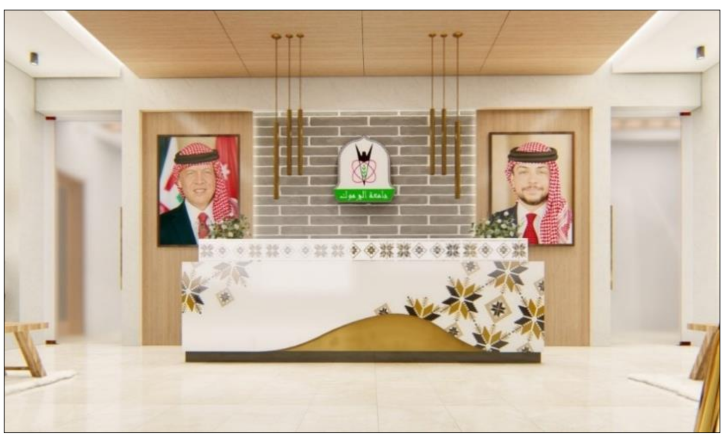
- **المخطط العام واللقطات المنظورية للتصميم المقترح:**



الرسم (9): مسقط أفقي يوضح التصميم المقترح الجديد للتوزيعات الأساسية للخدمات في منطقة الإستقبال في مبنى رئاسة جامعة اليرموك. المصدر: من تصميم الباحثة.

وفيما يلي سيتم عرض لقطات منظورية لتوضح فكرة التصميم المقترح لمنطقة الاستقبال والكوريدور الداخلي للطابق الرئيسي في مبنى الرئاسة في جامعة اليرموك.

الرسم (10): لقطة منظورية أخرى للتصميم المقترح للشكل الخارجي لمبنى الرئاسة في جامعة اليرموك. المصدر: تصميم الباحثة.

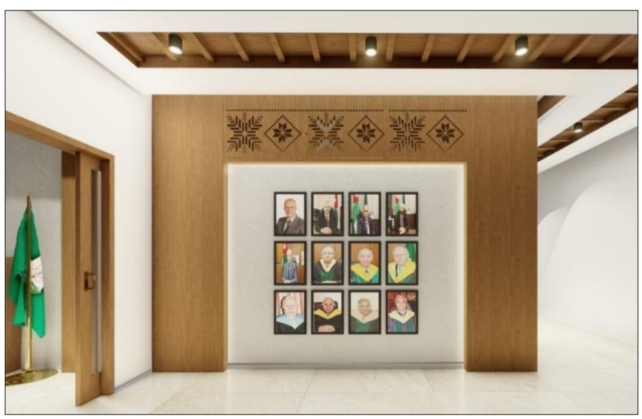


الرسم (11): لقطة منظورية لمنطقة الكاونتر في مبنى الرئاسة في جامعة اليرموك، توضح الاستلهام من مفردات ورموز التراث وتوظيفها في عناصر التصميم، بالإضافة إلى تكسية الجدار الخلفي للكاونتر بالحجر الأسود المستلهم من جدران البيوت التراثية، بأسلوب مجرد وبسيط كعنصر سيادة ولفت للناظر. المصدر: من تصميم الباحثة.

الرسم (12): يمثل الشكل لقطة منظورية لمنطقة الجلوس والانتظار في غرفة الاستقبال، توضح الاستلهام من القماش التراثي الشعبي وتوظيفه في الكنب، كما وتم نقش الحائط الجصي بنفس الزخارف الموجودة على منطقة الكاونتر والمستوحاة من أشكال ورموز الزي التراثي الأردني؛ وهذا يدل على التماثل في التصميم الداخلي، وتم اعتماد نحت الحائط على شكل أقواس، دليلاً على شكل الأقواس التي كانت موجودة ومصممة في حوائط وشبابيك البيوت التراثية القديمة، بأسلوب معاصر وغير مباشر، كما وتم إضافة عناصر وإكسسوارات تراثية وشعبية (كدلة القهوة النحاسية والفناجين التي تدل على الكرم والضيافة واستخدام القش والصحون النحاسية على الحوائط وغيرها من العناصر الشعبية) التي تدل على روح الانتماء والحنين إلى الماضي . المصدر: من تصميم الباحثة.

الرسم (13): لقطة منظورية كاملة توضح منطقة الاستقبال في مبنى الرئاسة من الداخل. المصدر: تصميم الباحثة.

الرسم (14): لقطة منظورية لمنطقة الموزع الخلفي (الكوريدور)، وكيف تم استلهام واختزال خطوط المهباش التراثي وتوظيفها على الحائط بأسلوب مجرد وبسيط يوحي بالحداثة وبألوان عصرية. كما تم وضع منضدة منجدة من قماش وجلود البسط الشعبي الأردني، كما وتم إضافة ثريات نحاسية لما لها من أهمية في تحقيق الراحة البصرية والهدوء النفسي. المصدر: تصميم الباحثة.



الرسم (15): لقطة منظورية لحائط الشرف، حيث تم وضع جميع صور رؤساء الجامعة السابقون والجدد، وتم تكسية إطار الحائط من خشب السويد المنقوش أيضاً بالزخارف التراثية. المصدر : تصميم الباحثة.

الرسم (16): لقطة منظورية توضح منطقة مدخل غرفة رئيس الجامعة، حيث تمت تكسية الحوائط بالدهان الجصي الأبيض وتكسية الأعمدة بخشب السويد، وإضافة شعار الجامعة على الحائط. المصدر: تصميم الباحثة.

الرسم (17):يمثل الشكل الأخير لقطة منظورية لمدخل وواجهة غرفة رئيس الجامعة، حيث تم توظيف عناصر التراث بأسلوب عصري وبصري غير مباشر. المصدر: تصميم الباحثة.

الرسم (18) يوضح مفردات التراث الأردني والخامات والعناصر المستلهمة في التصميم المقترح.

منهجية البحث

انتهج البحث المنهج **المختلط**، (النوعي والكمي) لتحقيق أهدافها. في الجانب **النوعي**، تم استخدام الوصف لدراسة التراث الأردني ووصف المباني الأثرية والتراث في مدينة إربد، بالإضافة إلى إجراء المقابلات الشخصية مع مجتمع الدراسة للحصول على آرائهم وتوجهاتهم. وفي المنهج التطبيقي، تم تطوير مقترح تصميمي يهدف إلى إحياء العناصر التراثية المحلية بأسلوب معاصر في مبنى رئاسة جامعة اليرموك في إربد. أما الجانب **الكمي**، استخدم البحث أداة الاستبيان لجمع البيانات من طلاب تصميم الداخلي في جامعة اليرموك، بهدف تقييم التصميم المقترح واستطلاع آرائهم حول موضوع الدراسة. ،كما يشار بالذكر أن الأبحاث من خارج الأردن تناولت فقرات بسيطة باستخدام التراث وتوظيفه بالتصميم الداخلي وندرة الأبحاث المحلية لذات الموضوع.

مجتمع البحث والعينة

تهدف هذه الدراسة إلى استكشاف توظيف التراث الأردني في التصميم الداخلي المعاصر وتعريف طلاب التصميم الداخلي في جامعة اليرموك بأهمية التراث وإمكانية تطبيقه. تم اختيار عينة من (104) طالبًا وطالبة في المدة ما بين (2020-2023) واستخدام استبانة لجمع آرائهم، بالإضافة إلى إجراء مقابلات مع مجموعة من المختصين في مجال التصميم والعمارة ومقابلات مع مستخدمي المبنى المراد إعادة تصميمه. تم جمع البيانات وتحليلها للتوصل إلى نتائج الدراسة واستخدامها في إعداد المقترح التصميمي.

أدوات البحث

تأخذ الدراسة عدة طرق وأدوات في عمليات جمع البيانات وتقييمها، سيتم استخدام الأدوات التالية:

- دراسات بحثية سابقة ذات الصلة.
- تحليل وتركيب عناصر ورموز وقيم التراث الأردني وتراث منطقة إربد.
- الملاحظة أثناء الزيارات الميدانية وتحليلها عبر التوثيق الصوري.
- إجراء المقابلات الشخصية لمعرفة آراء العينة التي تخلص نتائجها إلى تقديم المقترح التطبيقي.
- الحصول على كتابي تسهيل مهمة من جامعة عمان الأهلية إلى جامعة اليرموك.
- عمل مقترح تصميمي هدفه تحقيق الهوية من خلال إعادة إحياء العناصر التراثية المحلية في قالب معاصر وذلك عن طريق استخدام برامج التصميم المتخصصة.
- عمل "استبانة" على طلاب التصميم الداخلي في جامعة اليرموك (مكان الدراسة) واستطلاع آرائهم في تقييم التصميم المقترح.

طريقة تصحيح أداة البحث

تضمنت أداة الدراسة مجموعة من الأسئلة والجمل الخبرية بصورة استبانة تحتوي على جزئين، حيث يتضمن الجزء الأول المعلومات الديموغرافية للمبحوثين، بينما يتضمن الجزء الثاني على عبارات لقياس محاور الدراسة. حيث تم الاعتماد في قياس عبارات الاستبانة على مقياس ليكرت الخماسي للموافقة (موافق بشدة، موافق، محايد، غير موافق، غير موافق بشدة) حيث تم التصحيح لتعطى الدرجات (5،4،3،2،1) للمقياس على الترتيب، وقد تم احتساب المقياس من خلال استخدام المعادلة التالية:

الحد الأعلى للمقياس (5) - الحد الأدنى للمقياس (1) = (5 -1) = **1.33**

عدد الفئات المطلوبة (3)   (3)

ومن ثم إضافة الجواب (**1.33**) إلى نهاية كل فئة.

صدق أداة البحث

لغرض التحقق من الصدق الظاهري للدراسة (Face Validity)، تم قياسه من خلال عرض محتويات الاستبانة على مجموعة من المحكمين والأكاديميين من ذوي الخبرة والمعرفة في المجال؛ بهدف التحقق من انتماء الفقرات إلى متغيرات ومحاور أنموذج الدراسة، والأخذ بعين الاعتبار جميع ملاحظاتهم من حذف وتعديل للفقرات، لتتكون بعد ذلك الصورة النهائية لأنموذج الاستبانة.

الأساليب الإحصائية المستخدمة لأغراض تحليل بيانات الاستبانة

جرى معالجة البيانات إحصائياً من خلال استخدام برنامج (Statistical Package for the Social (SPSS، حيث تم استخدام بعض الأساليب الإحصائية التالية:

- الجداول التكرارية (Replication Tables) والنسب المئوية (Percentages).
- المتوسط الحسابي (Arithmetic Mean).
- الانحراف المعياري (Standard Deviation).
- معامل كرونباخ ألفا (Cronbach's Alpha).
- معامل الارتباط بيرسون (Person Correlation)، والاختبار وإعادة الاختبار (Test-Retest).

نتائج تحليل الاستبانة

جدول (5): المعلومات الديموغرافية لعينة الدراسة

الخاصية الشخصية	الفئات	التكرار	النسبة	الرسم البياني
التخصص	التصميم الداخلي	93	%89.4	
	غير ذلك	11	%10.6	
	المجموع	**104**	**%100**	
الجنس	ذكر	63	%60.6	
	أنثى	41	%39.4	
	المجموع	**104**	**%100**	
الفئة العمرية	من 18 - 24	69	%66.3	
	24 - فأكثر	35	%33.7	
	المجموع	**104**	**%100**	
سنوات الدراسة	**سنة أولى**	9	%8.7	
	سنة ثانية	33	%31.7	
	سنة ثالثة	17	%16.3	
	سنة رابعة	45	%43.3	
	المجموع	**104**	**%100**	

بعد دراسة وتحليل المتغيرات الديموغرافية في الجدول السابق يلاحظ بأن:

- غالبية المشمولين بالدراسة هم حملة شهادة التصميم الداخلي بنسبة 89.4%، مما يعكس أن مجتمع الدراسة ينتمون لنفس التخصص وهو التصميم الداخلي.
- الفئة العمرية بين 18 و24 سنة تشكل النسبة الأعلى بنسبة 66.3%، مما يشير إلى أنهم طلبة بكالوريوس ما زالوا على مقاعد الدراسة. بينما الفئة العمرية فوق 24 عامًا تمثل طلاب الماجستير بنسبة 33.7%
- الطلاب الحاصلين على شهادة البكالوريوس يشكلون 75% من عينة الدراسة، بينما حاصلي الماجستير يشكلون 25%، مما يظهر أن مجتمع الدراسة يتبع الدرجة الجامعية الأولى.
- أكثر فئة دراسية هي السنة الرابعة بنسبة 43.3%، مما يشير إلى أن أغلبية المشمولين بالدراسة في السنة الرابعة من مسار دراستهم.

وقد تم حساب المتوسطات الحسابية والانحرافات المعيارية **لتقديرات أفراد عينة الدراسة** على فقرات كل محور على حدة، حيث كانت على النحو التالي:

جدول (6): حساب المتوسطات الحسابية والانحرافات المعيارية **لتقديرات أفراد عينة الدراسة**

الرتبة	الرقم	الفقرات	المتوسط الحسابي	الانحراف المعياري	الدرجة
1	1	يعتبر التراث هو كل ما خلفته الأجيال السالفة في مختلف الميادين المادية والفكرية والمعنوية .	4.54	.573	مرتفعة
2	2	يجسد التراث هوية المجتمع المتوارثة من الأجيال السابقة وهو مبعث فخر واعتزاز لهم .	4.50	.607	مرتفعة
3	3	من أنواع التراث؛ التراث الملموس (مادي) الظاهر للعيان، مثل المباني الأثرية، الحرف التقليدية، الأزياء الشعبية.. إلخ	4.42	.602	مرتفعة
4	5	من أنواع التراث، التراث غير الملموس (غير مادي) المتمثل بكل ما يحويه من دين وعادات وتقاليد ونمط فكري ... إلخ	4.42	.634	مرتفعة
5	4	عناصر التراث يقصد بها المفاهيم المرتبطة بتوظيف التراث والتي تتمثل في (الطابع، الهوية، الطراز) .	4.38	.713	مرتفعة
–		**المتوسط العام**	**4.45**	**.449**	**مرتفعة**

الرتبة	الرقم	الفقرات	المتوسط الحسابي	الانحراف المعياري	الدرجة
1	10	من عناصر التراث الأردني المادي؛ الأزياء الشعبية التراثية للرجال والنساء.	4.57	.535	مرتفعة
2	11	من عناصر التراث الأردني المادي؛ الأدوات التراثية التي تدل على تراث الأردن الشعبي الأصيل، ومنها المهباش لطحن حبوب القهوه، ودلة القهوه والبساط الأردني بألوانه الحمراء وغيرها، بالإضافة إلى البيت الأردني مثل بيت الشعر.	4.49	.668	مرتفعة
3	6	التراث في الأردن هو موروثات تعكس الأصالة وتحمل عبق الماضي ونكهة البوادي والأرياف وذكريات الآباء والأجداد, ففيها صفات الكرم والشهامة .	4.46	.538	مرتفعة
4	9	من عناصر التراث الأردني غير المادي؛ العادات والتقاليد الشعبية، كالأطعمة المشهورة مثل المنسف، والطقوس المختلفة كالأفراح والأفراح الاجتماعية المختلفة مع الأغاني والموسيقى الشعبية	4.46	.622	مرتفعة

مرتفعة	.709	4.36	من عناصر التراث الأردني غير المادي؛ القصص الشعبية والشعر والنثر والأدب، الأهازيج، والدين بأركانه وأماكنه المقدسة.	8	5
مرتفعة	.721	4.25	التنوع الجغرافي لأقاليم ومحافظات الأردن انعكس إيجابياً على تراثه الحضاري، وهذا التنوع صاحبه تكامل في عناصره التراثية.	7	6
مرتفعة	**.443**	**4.43**	**المتوسط العام**	–	

مرتفعة	.520	4.54	من معالم التراث في مدينة إربد، البيوت والمتاحف التراثية القديمة، كمتحف دار السرايا وبيت النابلسي.	12	1
مرتفعة	.756	4.39	يعد الزي التراثي الأردني (الثوب) في مدينة إربد عنصراً أساسياً في المناسبات الشعبية والمجتمعية.	14	2
مرتفعة	.782	4.28	تعد العادات والتقاليد في مدينة إربد امتداداً للتراث المتوارث فيها قديماً.	15	3
مرتفعة	1.068	3.82	يشكل الطراز (المشهد) العمراني في مدينة إربد امتداداً للتراث المعماري فيها قديماً.	13	4
متوسطة	1.113	3.25	تقوم البلديات (بلدية إربد) بإعادة إحياء التراث من خلال توظيفها في عناصر مختلفة كالأماكن العامة وواجهات المباني وغيرها.	16	5
مرتفعة	**.509**	**4.06**	**المتوسط العام**	–	

مرتفعة	.531	4.60	استخدام الألوان التراثية في التصاميم الحديثة جزء من إحياء وتوظيف التراث.	19	1
مرتفعة	.649	4.58	استخدام العناصر التصميمية المستوحاة من البيوت التراثية في المنطقة مثل الأعمدة، الأبواب الخشبية العالية الارتفاع، الأقواس، فتحات الشبابيك؛ هي جزء من إحياء وتوظيف التراث.	21	2
مرتفعة	.735	4.56	إعادة استخدام النقوش القديمة وتوظيفها في التصاميم الحديثة جزء من إحياء وتوظيف التراث.	22	3
مرتفعة	.573	4.54	استخدام عناصر من التراث في مجال التصميم الداخلي أمر يحتاج إلى التركيز والدراسة حتى لا يدخل بشكل عشوائي ومسيئة للتراث ولا يحقق هدفه بالتصميم الداخلي.	18	4
مرتفعة	.591	4.48	استخدام الخامات التراثية في التصاميم الحديثة، كالحجر (الأسود والأبيض)، الأقمشة الملونة والمطرزة برموز تراثية، الفسيفساء الزجاج الملون وغيرها من الخامات هي جزء من إحياء وتوظيف التراث.	20	5
مرتفعة	.754	4.38	يحاول المصمم الداخلي المعاصر الاستلهام من قيم وعناصر التراث في محاولة للبحث عن الهوية، وإيجاد خصوصية تشابهت فيها الأشكال وامتزجت حتى فقدت خصوصيتها إلى حد كبير، وأصبحت لا تعبر عن شخصية المصمم وبصمته المميزة.	17	6
مرتفعة	**.474**	**4.52**	**المتوسط العام**	–	

1	25	تؤيد تدريس التراث وعناصره في المؤسسات التعليمية .	4.47	.812	مرتفعة
2	23	من أهم المؤسسات المسؤولة في توظيف وإحياء التراث هي السياحة والمؤسسات التعليمية (مدارس، جامعات، وغيرها)	4.45	.695	مرتفعة
3	27	ندرة وجود مشاريع تصميم داخلي ذات علاقة بالتراث وعناصر التراث.	4.36	.835	مرتفعة
4	26	تحرص على استخدام العناصر التراثية في مشروعك التخرج أو في تصميمك بأسلوب يواكب الحداثة.	4.34	.877	مرتفعة
5	24	يتم تدريس التراث والهوية بشكل عام في المساقات التعليمية في الجامعات والمؤسسات التعليمية.	3.30	1.069	متوسطة
–		**المتوسط العام**	**4.18**	**.500**	**مرتفعة**

- **نتائج تحليل المحاور:**

أظهرت الدراسة أن تقييم الطلاب لمحاور الدراسة المتعلقة بالتراث، بما في ذلك فهمهم للتراث بشكل عام وخاص، ومعرفتهم لمعالم التراث في مدينة إربد، وتوظيف التراث في التصميم الداخلي، كانت مرتفعة وقوية نسبياً. تراوحت المتوسطات الحسابية بين (4.06 - 4.52) مع انحرافات معيارية تراوحت بين (0.474 - 0.509) وبنسبة موافقة عالية وصلت إلى (87.4%). تقديرات الطلاب للمحور الذي يتعلق بـ "توظيف التراث في التصميم الداخلي" كانت في المرتبة الأولى بأعلى متوسط حسابي (4.52) ونسبة مئوية وصلت إلى (95.3%)، بينما كانت تقديراتهم للمحور الذي يتعلق بـ "معالم التراث في مدينة إربد" في المرتبة الثانية بمتوسط حسابي (4.06) ونسبة مئوية وصلت إلى(74.6%)

- **تحليل المقابلات الشخصية ونتائجها:**

أجريت مقابلات شخصية لـ 41 شخصًا من خلفيات مختلفة في مجال العمارة والتصميم الداخلي، بما في ذلك أكاديميين ومعماريين ومصممين يعملون في المكاتب الهندسية والمؤسسات الخاصة. تم جمع خصائص العينة الديموغرافية مثل (الجنس، العنوان، المهنة، التخصص، وعدد سنوات الخبرة). كما أجريت مقابلات شخصية ثانية وجهاً لوجه مع 7 موظفين إداريين يعملون في مكان الدراسة (الطابق الرئيسي لمبنى الرئاسة في جامعة اليرموك)، وتم جمع خصائصهم أيضًا.

تم طرح (4) أسئلة في المقابلات الأولى تم تصميمها مسبقاً من قبل الباحثة وعرضها على لجنة مختصة قبل البدء بعملية المقابلات؛ وذلك للتأكد من الأثر الراجع لموضوع الدراسة (إمكانية تطبيق العناصر التراثية البصرية في التصميم الداخلي المعاصر)، ومن ثم تحليل تلك المقابلات الشخصية ضمن جدول، واستخدام التكرار والنسبة المئوية لتمثيل آراء أفراد العينة، والتي من أجلها تؤكد على أهداف الدراسة وتساعد لبيان صحة الفرضيات.

جدول (7): تحليل المقابلات الشخصية . (N=41).

الرقم	السؤال	عدد التكرار للآراء			النسبة المئوية
		موافق	محايد	غير موافق	
1	ما رأيك بموضوع الدراسة، وهل يعتبر من المواضيع المهمة والملحة بهدف إيجاد الهوية في التصميم الداخلي المعاصر ؟	38	2	1	%92
2	بخبرتك ، هل يمكن أن تخبرنا عن التراث المحلي في الأردن، وما هي العناصر التراثية المحلية التي تتميز بها المنطقة ؟	35	2	4	%85
3	باعتقادك، ما تأثير تعزيز الهوية المحلية على مستخدمي الفراغات الداخلية في الأبنية التعليمية؟	36	2	3	%87
4	نشاهد في بعض التصاميم الداخلية الرائجة في الأردن افتقارها في توظيف التراث المحلي . برأيك ما السبب؟	40	1	0	%98

جدول (8): تحليل المقابلات الشخصية الثانية . (N=7).

الرقم	السؤال
1	ما رأيك في التصميم الجديد للمكان؟ وهل باعتقادك يعكس عناصر التراث الأردني بشكل معاصر في نفس الوقت؟
2	كيف تعتقد أن التصميم الجديد سوف يؤثر على بيئة العمل والمزاج العام للموظفين؟
3	باعتقادك، ما هي المشكلات والتحديات التي قد تواجه تطبيق التصميم المقترح في المكان؟

- **نتائج تحليل المقابلات:**

1- أجمع المبحوثين في المقابلات الشخصية، والذي بلغ عددهم (41) مبحوث؛ على اهتمام المجتمع الأكاديمي والعملي للتطرق لمثل هذه المواضيع من الدراسة، ألا وهي "تطبيق العناصر التراثية البصرية لتعزيز الهوية في التصميم الداخلي المعاصر"، حيث شكلت النسبة المئوية للتأييد (%92).

2- وافقت نسبة كبيرة من المبحوثين في المقابلات الشخصية التي بلغت حوالي (87%)، على أن الأردن غني بالتراث ويضم العديد من العناصر التراثية المعنوية والمادية، تعود لتواجد حضارات في المنطقة وضمن أزمنة مختلفة ومتتالية، وعلى أنه يوجد تأثير بصري بتعزيز الهوية المحلية على مستخدمي الفراغ الداخلي في الأبنية التعليمية، مما يزيد بروح الانتماء والولاء والاعتزاز والفخر للمكان، وتضفي ذاكرة بصرية لتواصل الماضي مع الحاضر المعاصر.

3- شكلت أكبر نسبة تأييد للمبحوثين في المقابلات الشخصية والتي بلغت بنسبة (98%)، على الافتقار الكبير لدمج التراث والهوية في بعض التصاميم الداخلية الرائجة في الأردن، ويعود السبب الرئيسي الذي أجمعوا عليه هو (السعي وراء العولمة)، وهذا يفيد بأهمية التطرق لمثل هذه الدراسات لمحاولة الوعي بأهمية دمج التراث في التصميم الداخلي والعمارة؛ للحفاظ على الهوية أو جزء منها وبشكل يواكب متطلبات العصر.

4- شكلت نسبة تشجيع كبيرة للمبحوثين في المقابلات الشخصية الثانية على الإعجاب والاستحسان للتصميم المقترح الجديد وبتناغم العناصر التراثية والمعاصرة، واستخدام الألوان والزخارف الأردنية التقليدية بشكل مبتكر وجذاب.وأجمع الأغلبية على أن التصميم المقترح الجديد قد يعكس التوقعات الإيجابية على بيئة العمل والمزاج العام للموظفين، مما قد يسهم في تعزيز الروح المعنوية والإبداع والرفاهية في مكان العمل. وإنه من الممكن أن تظهر مخاوف وتحديات مشتركة

تتعلق بالتنفيذ والتكلفة، أو صعوبة تنفيذ العناصر التراثية بطرق معاصرة وتحقيق التوازن المطلوب.

- **مقارنة نتائج الدراسة بالأهداف:**

الهدف الرئيسي:

- **الهدف:** تحقيق الهوية من خلال توظيف العناصر التراثية الأردنية في التصميم الداخلي المعاصر.
- **النتيجة:** تم تصميم مبنى الرئاسة بشكل يعبر عن التراث الأردني وإربد بوضوح.

الأهداف الفرعية:

- تنمية الوعي الثقافي والحس الجمالي والتذوق الفني بهوية التراث الأردني المادي وغير المادي للمجتمع.

النتيجة: الطلاب والمجتمع يعبّرون عن إيجابيتهم تجاه التصميم ويشعرون بالوعي الثقافي.

- الكشف عن العناصر التراثية المحلية التي من شأنها تأمين مشهد بصري يدعو إلى الإيجابية في تصميم الفراغات الداخلية بأسلوب عصري وغير تقليدي.

النتيجة: تم التعرف على العناصر التراثية المحلية وتضمينها في التصميم بشكل ملائم.

- التأكيد على الأصالة وإحياء التراث والحفاظ عليه من الاندثار عن طريق النشر الأكاديمي، كمصادر توظيف عناصر التراث في تصميم داخلي مستحدث.

النتيجة: تم التأكيد على الأصالة وتحفيز الحفاظ على التراث.

- التعرف على تجارب عالمية ومحلية في المحافظة على هوية المجتمع في التصميم الداخلي والعمراني.

النتيجة: تم تحليل تجارب عالمية ومحلية واستفادة منها في التصميم.

- الخلوص بنتائج ومقترحات تطبيقية، لإنتاج تصميم داخلي محلي يواكب العصر وإمكانياته.

النتيجة: تم إعداد مقترح تصميم داخلي محلي معاصر.

الخلاصة:

يمكن القول أن النتائج تشير إلى تحقيق العديد من الأهداف التي وضعتها الدراسة، بما في ذلك توظيف العناصر التراثية بنجاح في تصميم مبنى الرئاسة وزيادة الوعي الثقافي وتحقيق الأصالة وتوجيه تجارب عالمية ومحلية في المحافظة على هوية المجتمع.

توصيات البحث

- تأكيد تعزيز الهوية ومعرفة التراث في التصميم الداخلي.
- وضع رؤية تربوية شاملة لتعزيز الانتماء للتاريخ والحضارة والتراث في المناهج الدراسية.
- توفير فرص للتواصل والتفاعل المستمر مع الموظفين والطلاب للحصول على ملاحظاتهم.
- تبني ودراسة مشروع التصميم المقترح لتوظيف العناصر التراثية المحلية ووضع خطط لتطبيقه.
- التعاون مع فريق متعدد التخصصات لتحقيق التصميم الأمثل والتناسق مع الهوية الثقافية.
- زيادة الاهتمام بعمليات الترميم في البيوت التراثية في إربد والمدن الأخرى في الأردن.
- تشجيع الباحثين على إجراء دراسات تحليلية للتراث في مختلف مدن الأردن

- **المراجع العربية**

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PROTECTING, RESTORING AND COMMUNICATING CULTURAL HERITAGE IN LEBANON: FROM THE "SOAB PROJECT" TO THE USEK MUSEUM

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Abstract. The blast in the port of Beirut had catastrophic consequences not only in human, economic and social terms, but also caused an important crisis for the preservation of the vast cultural heritage in the Lebanese capital. In this context, an international agreement between the School of Conservation and Restoration of the University of Urbino, USEK and IIC-Beirut, called the SOAB project, has made it possible to establish a collaboration aimed at developing best practices for the recovery and restoration of movable works of art damaged during the traumatic event. The project is not only dedicated to the recovery of damaged heritage, but from a sustainable and long-term perspective it aims to produce a transfer of knowledge and skills for the training of professionals in the field of conservation and restoration in Lebanese territory. The first phase of project management and the hypothesis of a new data management model from the restoration laboratories made it possible to establish the first communication and dissemination activities of contents regarding the care of cultural heritage both with physical/analog methods and through digital media. Hopefully, the same methodology will be applied to the conservation of the USEK Museum collection, incorporating archaeology, ceramics, icon, painting, sculptures, metallics and contemporary art.

Keywords: *Beirut blast, Lebanese cultural heritage, conservation, restoration, digital documentation, dissemination.*

ملخص. إن الانفجار المدمر الذي وقع في مرفأ بيروت لم يتسبب فقط في معاناة إنسانية هائلة ومحنة اقتصادية واضطرابات اجتماعية، بل كان له أيضا تأثير عميق على الحفاظ على التراث الثقافي الغني للبنان. إدراكا للحاجة الملحة لحماية وترميم الأعمال الفنية التالفة، بدأ تعاون دولي بين مدرسة الحفظ والترميم بجامعة Urbino – إيطاليا وبجامعة الروح القدس - الكسليك والمعهد الثقافي الإيطالي في بيروت IIC. تهدف هذه المبادرة، المعروفة باسم مشروع SOAB إلى تطوير استراتيجيات فعالة لاستعادة وترميم الأعمال الفنية المنقولة المتأثرة بالحدث المأساوي. بالإضافة إلى جهود الترميم الفورية، يركز المشروع أيضا على نقل المعرفة وتنمية المهارات لتمكين تدريب المهنيين في مجال الحفظ والترميم داخل الاراضي اللبنانية.

مع بدء مشروع SOAB، ركزت المرحلة الأولى على الإدارة الفعالة للمشروع وتطوير نموذج شامل لإدارة البيانات. يضمن هذا النموذج المعلومات الضرورية المتعلقة بالأعمال الفنية التالفة يتم جمعها بشكل صحيح واستخدامها بشكل فعال لأغراض الترميم. من خلال اعتماد هذا النهج المنظم، يمكن للمشروع تنسيق الأنشطة المختلفة بسلاسة ونشر للمحتويات المتعلقة برعاية التراث الثقافي سواء بالطرق المادية / التناظرية أو من خلال الوسائط الرقمية.

بناء على النجاح والدروس المستفادة من المراحل الأولية سيتم تطبيق نفس المنهجية المستخدمة في مشروع SOAB للحفاظ على مجموعة متحف جامعة الروح القدس الكسليك الذي يضم مجموعة متنوعة من القطع الأثرية التي تشمل علم الآثار وأيقونات السيراميك واللوحات والمنحوتات والأشياء المعدنية وكذلك الفن المعاصر. من خلال دمج أفضل الممارسات، سيساهم مشروع SOAB في الحفاظ على هذه الأعمال الفنية القيمة
وترميمها لضمان استدامتها على المدى الطويل.

الكلمات المفتاحية: انفجار بيروت، التراث الثقافي اللبناني، الحفظ، الترميم، التوثيق الرقمي، النشر.

1. Introduction

The blast of the port of Beirut, in fact, has had catastrophic consequences not only in human, economic and social terms, but has also led to an important crisis for the protection of the vast cultural heritage in the Lebanese capital city. Lebanon has vast public and private collections of various artworks, from paintings on canvas to Orthodox icons, from ceramics to decorated metal, from old textiles to stone sculptures. However, not only is Lebanese artistic production little studied by the history of art, but also there are no professional figures in Lebanon such as conservators and restorers of cultural heritage capable of intervening on public and private collections both in terms of preventive conservation and of emergency safety measures following traumatic events. This lack of adequate professional figures manifested itself in a particularly dramatic way in the days following the port blast, when adopting standardized measures to secure the damaged assets was a major priority. Therefore, an international agreement between the School of Conservation and Restoration of the University of Urbino, the USEK and the IIC-Beirut, called the SOAB project, has made it possible to establish best practices for the recovery and restoration of movable works of art damaged during the traumatic event. The project is not only functional to the recovery of the damaged heritage, but in a sustainable and long-term perspective it aims to produce a transfer of knowledge for the training of professionals in the field of conservation and restoration in the Lebanese territory, thanks to the institution, right at the USEK, of a B.A. 3-years course in "Conservation, Restoration of Cultural property and sacred art", the first Conservation and Restoration course in the whole Middle East, based on Italian restoration methods capable of using a scientific and standardised approach to intervention. The methodology used, and on which the students are trained, provides for the application of a standardized workflow that starts from the digital documentation of each artwork, passes through accurate non-invasive diagnostic investigations through the multispectral imaging technique and - where necessary - of the 3D survey and other scientific investigations, up to intervention choices weighted on the specific case and based on the scientific evidence that emerged during the analyses. The first phase of the project which ended in December 2022 made it possible to set up the first communication and dissemination activities of contents concerning the care of cultural heritage both in physical/analogue ways and through digital media. For the year 2023, this international collaboration aims to expand its horizons even further, through a work that takes as a case study the USEK museum, which recently acquired the entire art collection of Emile Hannouche, consisting on more than one thousand paintings on canvas and other typologies of artworks. Through the digital documentation for the conservation of each work of the museum collection, it will be possible to develop best practices for the long-term control of the works of art present, creating a small but innovative heritage digitization hub within the museum, in order to be able to make it available digitally outside the Lebanese borders.

2. Our research question: how to take care of the Lebanese heritage from the current crisis contexts up to a long-term perspective

The research presented here has its roots in an Italian-Lebanese international agreement for the training of future restorers in the Middle East area. The project, which began in 2016, has undergone a significant acceleration due to the urgent need to safeguard the historical and artistic heritage after the explosive event that hit the Lebanese capital in 2020. For this reason, we will start by analyzing the context and consequences of this traumatic event before arriving at the formulation of the research question that prompted the expert's team to set up a workflow capable of responding to the needs of saving artworks in emergency contexts.
At 6:08 pm on August 4, 2020, 2,750 tons of ammonium nitrate seized by the Lebanese government in 2014 and stored in a container in Beirut Port without proper safety measures, caused a violent explosion. The event, dubbed the

"Beirut Port Blast," was estimated to be equivalent to a magnitude 4.5 earthquake, the largest non-nuclear explosion in history (Mady et al., 2020). In fact, the calculated aftermath was severe: 218 people died, approximately 7,000 were injured, 300,000 were displaced, a two-week state of emergency was declared throughout the city, and some 8,000 buildings were damaged. This damage, as well as the human, economic and material losses, also had implications from a historical and cultural point of view, as the districts most affected by the explosion (Gemmayzeh and Mar Mikhael districts, together with the Sursock district, part of the Ashrafieh residential area) are considered the center of the city's artistic and cultural scene (Chami&Rizk 2021) (Fig. 1). Due to historical political and social instabilities, we know that the city of Beirut in particular has been destroyed and rebuilt many times. However, the methodologies applied during the most recent reconstructions cannot be considered sustainable from the point of view of the preservation of the historical and artistic heritage, both in its individual evidence and in its close relationship with the complex urban fabric of the city.

Figure 1. The blast of the container in the port of Beirut and the dramatic consequences on historical buildings.

As we know, following the devastating civil war that spanned from 1975 to 1990, there arose an urgent need for the reconstruction and revitalization of the historic center. In response to this, a private company of French origin, known as SOLIDERE, monopolized the efforts. With the government's approval, SOLIDERE implemented controversial measures that allowed for the rapid redevelopment of Downtown Beirut and its Souks. However, this came at the cost of demolishing almost all of the pre-existing buildings, resulting in a district that became completely detached, both in terms of urban planning and its economic and social integration with the rest of the city

(Felix, 2019). Furthermore, the government has faced increased challenges in implementing policies and taking action due to the recent financial crisis that originated in 2019 and worsened as a result of the COVID-19 pandemic. Consequently, the responsibility of preserving cultural assets has largely fallen upon non-governmental organizations (NGOs) and UNESCO, who were the first to initiate efforts to rescue and safeguard these valuable cultural artifacts. The architectural heritage has been particularly vulnerable, with approximately 640 historic buildings suffering damage, 60 of which are at imminent risk of collapse, as estimated by UNESCO teams (Unesco, 2020).
The potential jeopardy extended beyond the plain buildings themselves. The city boasts an extensive archaeological legacy, diffused throughout the urban landscape and housed within four distinct archaeological museums: The National Archaeological Museum, the Archaeological Museum of the American University of Beirut, the Prehistoric Museum of the Saint Joseph University, and the in-situ Archaeological museum in the Crypt of the Orthodox Church of Saint George. Equally significant is the movable artistic heritage, comprising paintings and various other portable artworks, encompassing both religious and secular subjects. These valuable pieces were scattered across Beirut's territory, residing within churches and private collections alike. All these data, taken individually and collectively, already give an account of the complexity of intervention in such a situation. Although projects to secure and restore the architectural and archaeological heritage were immediately implemented by international organizations based on recognised standards (After the Damages, 2020), little or nothing was being done to reconstitute the movable/small-scale artistic heritage, and consequently to revitalize the artistic and cultural scene in the Lebanese capital, which with its heterogeneity of currents and styles constitutes still now a precious unicum in the whole Middle Eastern territory.
Up to the year 2022, thanks to individual and collective work mostly conducted by UNESCO, non-governmental organizations, research bodies and embassies, a lot of thing have changed and evolved from the initial situation, as Beirut is beginning to be reborn through some more culturally sustainable projects than what was obtained with SOLIDERE. Among the incredible amount of valuable projects for the rebuilding of Beirut, we cannot forget the LiBeirut Project by UNESCO, an initiative that aims to mobilize the international community to support the reconstruction of the city’s educational and cultural sectors, through some dedicated projects, which are divided into three main trajectories: restoring education (through an extensive rehabilitation work on different schools in Lebanon), supporting media (thus enabling safe and professional investigative journalism in Lebanon) and, most importantly, reviving culture. This last crucial point consisted in the digital documentation of the destructed buildings within the city of Beirut, made together with the Lebanese Directorate General of Antiquities (DGA). After processing more than 100,000 images, it was possible to create a geo-

referenced three-dimensional model of the Lebanese capital, which is crucial to the city's reconstruction, also with the aim of training future professionals in the fields of archaeology and geodesy. From this first step, together with the AUB, UNESCO created the Beirut Urban Lab, a project which initially had to map the buildings damaged by the explosion using an open and interoperable 2D geo-referenced software, cataloging them according to various criteria (state of conservation, district, architectural style, cultural context) (Fig. 2), and which in three years has become a digital space aimed at creating confrontation and dialogue between the two parts of the city (the Christian and the Muslim one) divided by the civil war and which the SOLIDERE project had failed to reconnect, through the safeguarding of the architectural and artistic heritage. Lastly, the recent reopening of the Sursock Museum and the Archaeological Museum of the AUB, with renewed exhibition itineraries which also include the story of the explosion in the narration of the works preserved, seem to confirm a logical junction that is fundamental for us: the disaster contributed to create a new collective awareness, which sees in the care of the Lebanese heritage a fundamental element of dialogue between parts that, until now, seemed irreconcilable.

From this last statement, we started elaborating our research question, which is as follows: how can we, as the first school of conservation and restoration of cultural heritage in the whole Middle East, develop a working method that allows for the rapid rescue of damaged movable heritage and that simultaneously takes into account the limited resources in the field and the need to train future professionals in the world of restoration? Can this process be replicable in other contexts? Can it contribute to create new awareness in the population around the need for daily and preventive conservation of cultural heritage?

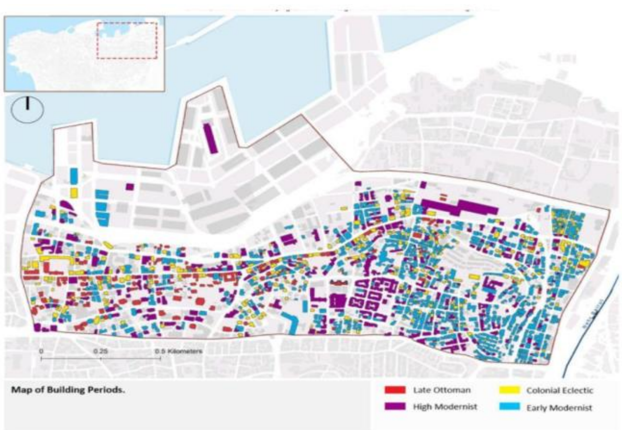

Figure 2. The georeferenced database mapping historical buildings in Beirut affected by the blast (Source: Beirut Urban Lab).

3. A new methodology: starting the SOAB project

We have already mentioned how in the UNESCO LiBeirut project the re-foundation of education plays a fundamental role in the formation of a collective critical thought, useful in the long term for the recognition and protection of the Heritage. In addition to the educational and academic importance of these processes, we must also take into consideration the enabling tools and technologies that the contemporary and digital world in which we live offers us. The enormous potential of digital documentation and 3D surveying has already been globally recognized by the scientific communities for some years, and this area of the world in particular has seen the realization of some UNESCO projects around this theme. Digitizing heritage, with various technologies, allows not only to map, monitor and document it, but also to make it usable even by non-professionals and remotely, effectively constituting an enabling practice with respect to the great issue of enhancing the world heritage (Vileikis et Al., 2023).
Analyzing the question from the point of view of the restorer, the digital documentation of the movable heritage provides a very useful tool also from the point of view of conservation, providing data which, if interpolated with other historical-artistic and diagnostic information, allow to evaluate mechanisms deterioration and to plan a restoration intervention. In turn, digitally produced conservation data can also be made accessible to the public to raise awareness of conservation and restoration issues. (Baratin et Al., 2023).
These considerations allow us to focus on the knowledge gap which is present within all the Beirut revitalization projects carried out so far, while being aware of their extremely high value: in fact, they consider the movable heritage and the need for its conservation to be marginal, not training future professionals on the topic of conservation and restoration (Orbasli, 2007). The issue of training conservators and restorers, especially for movable heritage which is the least protected with respect to architecture and archeology, seems to be a common problem for the entire Middle Eastern area. For this reason, in 2016, an international agreement between the School of Conservation and Restoration of the University of Urbino and the USEK-Holy Spirit University of Kaslik helped create a Bachelor program in Conservation, Restoration of Cultural Property & Sacred Art at the USEK (about 20 minutes north of Beirut), according to the guidelines of the European organisation ECCO-ENCORE and in particular according to the Italian training standards. According to ICCROM, this course can be considered the first one settled down in the Middle East area covering the issues of movable artistic heritage,

and not only archaeology or built heritage, for which different programmes are already existing (ICCROM, 2016).

The Bachelor is intended as a mix of historical-artistic, scientific and technical-practical subjects, as this approach helps on the one hand the transfer of skills in the conservation and restoration of movable heritage following the traditional Italian methodology, and on the other it forms new sensitivities capable of building, in the long term, a local collective awareness with respect to the Lebanese heritage. Within this context, the SOAB project was activated during the second half of 2022 with the cooperation of the Italian Cultural Institute in Beirut, to restore a group of artworks by private collectors from the Sursock district and damaged during the port blast, as well as other religious works deposited in the USEK Museum and owned by the Lebanese Maronite Order. In total, five works were restored by UNIURB restorers during the teaching modules for USEK students in October - December 2022, and many others coming from the Maronite Order and the USEK Archeological Museum underwent different kinds of interventions throughout 2023.

Given the contingencies, the need to implement an agile and replicable method for the entry, preliminary evaluation, intervention and return of each work played a role of fundamental importance. It is to note that the lebanese government ratified in 2001 a document (Chartre du citoyen pour le patrimoine, 2001) in which the concepts of documentation, preservation, conservation and restoration of cultural heritage are mentioned, but they only refer to archaeological/built historical sites and they do not cite how to practically perform the operations required. In the same document, the USEK - Holy Spirit University of Kaslik is mentioned as one of the institutions responsible for the settlement of methodologies for heritage documentation, presentation and conservation. Over the years, in fact, the Maronite Order created some standardised datasheets to catalogue heritage sites and objects belonging to the Maronite Church: those datasheets require generic information about the site/artwork and do not concentrate enough on the conservative issues; moreover, the analogical support (i.e. paper datasheets, complied by hand) do not allow an easy documentation of the different states of the artwork during time and an easy interoperability between professionals. For those reasons, this method was considered unsuitable for the SOAB project, as the artworks involved needed to be recorded before, during and after the intervention, and the information needed to be shared between restorers, restoration students, diagnosticians and owners. To do that, the restorers have developed a workflow, which is based on the digital documentation of both the preliminary evaluation of the state of conservation and the restoration intervention and allows for the generation of information material for technical sheets and end-of-work reports, but at the same time allows translation of this material from a popular point of view, making the public aware on what was happening inside the laboratories. Although different softwares for digital documentation of conservative data for cultural objects exist, like the italian SICaR, or Articheck or others (Siotto et Al, 2016; Baratin & Cattaneo, 2016), the digital documentation method applied in this context is based on the CDR web-software, available in several languages (Italian, English, French, Spanish).

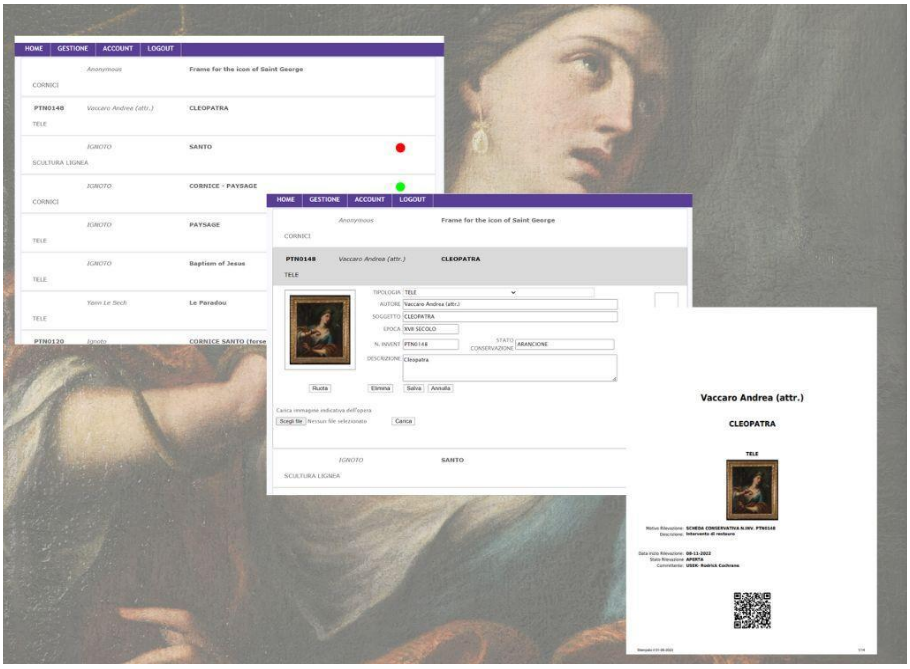

Figure 3. Some views of the CDReport web software, from the list of the artworks documented ('owner' and 'collaborator' view), to the single technical datasheet ('owner' and 'collaborator' view), up to the PDF print (to be sent to the owner of the artwork as a final technical report).

The CDR - Conservation Digital Report system constitutes an operational support tool for the management of documentation with a view to being able to satisfy archiving protocols, documentation of the interventions and condition reports, considering the specific purposes of each datasheet. The system is hierarchical (i.e. it can be accessed with 'owner', or 'collaborator' or 'visitor' profiles, allowing a different degree of data uploading possibilities) and divided by types of works of art, and uses a standardised datasheet structure to facilitate the management and input of textual and graphic information such as images, 3D models and graphic mapping in the document files (Gasparetto, 2022).

According to a standardized documentary protocol that we have already validated in the recent fields of experimentation of the School of Conservation and Restoration (Baratin et Al., 2022), we defined a fixed workflow for everyone of the artworks involved in the SOAB project, taking into account the limited availability of time, professionals and materials. While the CDR served as a roadmap to be used in every single step of intervention, the "journey of the artworks" inside the USEK laboratories was divided as shown in Table 1, following this precise order. Technically, each artwork was firstly created within the CDR platform through the 'owner' profile; secondly, the 'owner' profile enabled one 'collaborator' profile to enter information about the artwork in the datasheet (note that the 'collaborator' profile was property of the restoration instructor within the USEK laboratory, i.e. in this case Veronica Tronconi). In this period, no 'visitors' profiles were created; however it has been hypothesized to open up a 'visitor' profile for USEM Museum members, to enable them to see the restoration works done on the artworks of their property. Finally, once the datasheet was completed and the restoration intervention was considered finished, a PDF print of all the information uploaded on CDR was printed, as it served as a technical final report to send to the owner of the artwork.
The elaborated workflow made it possible to subject the first 5 works of the SOAB project to intervention in three months (Fig. 4), and it also proved effective in other work contexts experienced during the year 2023, when the students applied the methodology for completing their final thesis projects.

TABLE 1. The methodology and workflow applied to every artwork which underwent a restoration intervention within the SOAB project.

Operational phase	**Professionals involved**	**Type of CDR datasheet produced**
Transport to the USEK laboratory	Restorer Transporters	
Photographic documentation before the intervention	Photographer Diagnostician	
Multispectral Imaging	Diagnostician	CDR conservative datasheet
Historical artistic analysis	Art historian	
Evaluation of the State of	Restorer	

Operational phase	**Professionals involved**	**Type of CDR datasheet produced**
conservation		
Restoration intervention	Restorer	
Photographic documentation during and after the intervention	Restorer Photographer	CDR restoration intervention datasheet
Final exhibition set up	Restorer Transporters	
Transport back to the owner	Restorer Transporters	CDR Condition Report datasheet
Conservative protocol	Restorer	

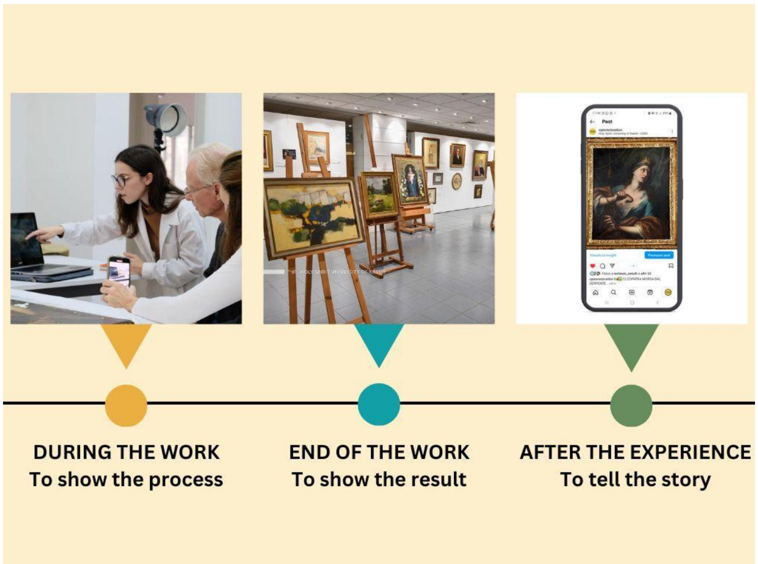

Figure 4. Restoration session with a student, which is trained to work under the microscope for the tear mending phase.

4. The SOAB project: first results in dissemination practice

In parallel with the data management processes and the carrying out of the restoration interventions, it was clear from the premises of our research question that these processes had to be fully accessible to the Lebanese community, in various forms, to create awareness around the heritage starting from the restoration laboratory. In a nutshell, we wanted to apply different onsite and online communication strategies to this context as well, using the data already acquired and systematized to make them available to the public, enabling a new form of understanding of their heritage (Baratin et Al., 2022).
As the conservative protocol established is really complex as it is built out of different steps, it was found necessary to implement dissemination strategies during the work (to show the process), at the end of the work (to show the result), and after the whole experience (to tell the story) (Fig. 5).
In order to dispel the misconception that heritage restoration was solely an artistic endeavor centered around traditional techniques and materials, it was crucial to demonstrate the workflow involved.

Figure 5. A graphic representation of the communication/dissemination project, divided into three phases.

As a result, the restoration laboratory was made accessible, allowing USEK students and high school students to observe the ongoing progress and receive guided tours from the restorers every Friday morning. Additionally, pre-arranged visits were scheduled on other workdays for visiting professors from USEK or other Lebanese universities, religious figures, workers from the Italian Embassy, private collectors invested in the project, as well as the owners of the artworks undergoing restoration. The objective of this approach was to highlight the collaborative nature of heritage restoration and expand the comprehension of its multidisciplinary aspects. In a more recent period in Lebanon, the UNIURB restorers further enhanced the quality of these visits and designated them with a special name: "Meet a restorer: how to care for Lebanese heritage". On December 15, 2022, upon the completion of the restoration work on the five pieces for the SOAB project, an exhibition was inaugurated at the USEK Museum to showcase the restored works to the public, known as the "Peace by piece" exhibition. The entire event was overseen by the restorers, who not only designed the exhibition space but also presented the work to observers. They utilized a graphic identity and various aids for visitors, such as videos and before/after photographs (the same ones previously recorded in the CDR restoration intervention datasheet), to convey the interventions that were carried out, all in line with the desired tone of the day, which was intended to be as a moment of identity and renewal following the catastrophic explosion.
After the completion of the restoration works in Lebanon, a concise online narrative was developed through the Instagram Open Restoration page to document the process. The documentation used during the restoration and registered in the different CDR datasheets has now transformed into a means of communication, enabling the creation of content that narrates the story of each restored work. The objective of this initiative was twofold: to engage both the Lebanese and Italian audiences, which is why a bilingual Italian/English narration was chosen. Despite limited resources and data available to the restorer and communicator, these initial outputs demonstrate the effectiveness of a validated approach in making information more accessible to a wider public. This approach empowers the public to actively participate in the preservation of their heritage, transforming them from passive observers to proactive contributors. While there is still potential for further content production in Open Restoration, these early results highlight the significance of an inclusive and engaging approach.

5. Conclusions and future perspectives

In the latter part of 2022, the SOAB project was initiated as the sole international endeavor taking place within Lebanon having the main aim of providing comprehensive training to local experts in the realm of conservation and restoration.

During the months of June 2022 and May 2023, a group of five students from the Bachelor of Arts in Conservation, Restoration of Cultural Property & Sacred Art program at USEK engaged in comprehensive discussions regarding their final theses. These discussions served to demonstrate the efficacy of the methodologies employed within the laboratories at USEK in training aspiring restorers. It is crucial to recognize that raising awareness about the significance of heritage preservation extends beyond immediate crisis situations. This process requires long-term commitment, and we firmly assert that sustained efforts from UNIURB should prioritize this objective.

Our initial priority is to emphasize the transition from restoration to conservation. Despite its apparent contradiction, the true catalyst for transformation lies in implementing the aforementioned workflow and data management techniques within the realm of the USEK Archaeological Museum. This approach ensures the active preservation of over a thousand artworks currently housed in storage, which have never been cataloged or documented from a technical point of view with regards to their conservative condition.

The approach utilized in this context is highly reliant on digital means. It prioritizes the development of diverse outputs and occasions for both online and onsite engagement, as opposed to a unidirectional information system. This methodology enables the establishment of a standardized workflow that effectively handles the technical and scientific data derived from a restoration or conservation site. Subsequently, these findings can be transformed into informative content specifically conveyed to the non-expert public. We firmly believe that this approach holds immense potential for storytelling purposes as well.

After having expanded the horizons of the initial project throughout 2023, through some emergency interventions within the exhibition path of the USEK museum, which recently acquired the entire art collection of Emile Hannouche, we think that it is needed now to move from “emergency situation protocols” to “preventive conservation protocols”, both in museums, private collections and other cultural institutions, still taking as a first case study the USEK museum and its diverse collection. By implementing digital documentation for the preservation of every piece in the museum's collection, it will be feasible to establish effective strategies for the ongoing maintenance of the artworks (Fig. 6).

Figure 6. The Emile Hannouche Collection within the USEK Archeological Museum deposit.

This will involve the establishment of a compact yet pioneering digitization center within the museum premises, allowing for the digital accessibility of the collection beyond the confines of Lebanon.
In order to gain a greater understanding of the influence of this process, future research perspectives propose a qualitative-quantitative assessment. This assessment aims to measure the extent to which social consciousness is raised regarding the important role of the restorer as well as the imperative to preserve the nation's invaluable and varied works of art, as these artworks require daily conservation efforts due to their irreplaceable nature.

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ASSESSMENT OF USER INTERACTION USING PHOTOGRAMMETRY AS A TOOL FOR PRESERVING ROSETTA STONE

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Abstract. Many Egyptian artifacts, statues, and monuments are displayed in museums around the world, where most of them are illegally transferred. One of these monuments is the Rosetta stone, which is located at the British Museum in London, where Egypt has been demanding its return for years. Many applications such as Photogrammetry can be used to temporarily document, restore, and preserve any missing or damaged monuments that no longer exist. The paper aims to assess the user interaction with the absence of unattainable/looted artifacts focusing on the Rosetta stone using photogrammetry as a tool. This would increase users 'awareness and interaction with their heritage through the integration of virtual and augmented techniques. The method used Recap Autodesk software as a guideline to generate an accurate 3D model of the stone to simulate a real environment. 3D Vista software and Vuforia Unity plugin were used for virtual and augmented user interaction. A survey has been done on 36 participants to test the model for assessing their interaction. The results recorded high interaction and satisfaction from the participants through experiencing the virtual tours of the Rosetta stone in its actual environments via augmented reality. Introducing Photogrammetry techniques would not only help to preserve the missing pieces but also reduce the boundaries between various generations and their heritage. Moreover, VR and AR can help museums attract new audiences and encourage repeat visits from existing ones. Additionally, these technologies can help museums reach a wider audience by providing virtual tours and exhibits that can be accessed from anywhere in the world, making it easier for people to engage with art and culture regardless of their location.

Keywords: Virtual heritage, photogrammetry, Virtual reality, Augmented reality, User interaction.

ASSESSMENT OF USER INTERACTION USING PHOTOGRAMMETRY AS A TOOL FOR PRESERVING ROSETTA STONE

ملخص. يتم عرض العديد من القطع الأثرية والتماثيل والآثار المصرية في المتاحف حول العالم، حيث يتم نقل معظمها بشكل غير قانوني. ومن هذه الآثار حجر رشيد الموجود بالمتحف البريطاني بلندن، حيث تطالب مصر منذ سنوات بإعادته. يمكن استخدام العديد من التطبيقات مثل التصوير المساحي لتوثيق واستعادة والحفاظ على أي آثار مفقودة أو تالفة لم تعد موجودة. تهدف الورقة إلى تقييم تفاعل المستخدم مع عدم وجود قطع أثرية غير قابلة للوصول/منهوبة مع التركيز على حجر رشيد باستخدام المسح المساحي كأداة. وهذا من شأنه زيادة وعي المستخدمين وتفاعلهم مع تراثهم من خلال دمج التقنيات الافتراضية والمعززة. استخدمت الطريقة برنامج ريكاب أوتوديسك كمبدأ توجيهي لإنشاء نموذج ثلاثي الأبعاد دقيق للحجر لمحاكاة بيئة حقيقية. تم استخدام برنامج فيستا ثرى دى والمكون الإضافي فيوفوريا يونيتي لتفاعل المستخدم الافتراضي والمعزز. تم إجراء مسح على ٣٦ مشاركًا لاختبار النموذج لتقييم تفاعلهم. وسجلت النتائج تفاعلاً ورضا عالياً من قبل المشاركين من خلال تجربة الجولات الافتراضية لحجر رشيد في بيئاته الفعلية عبر الواقع المعزز. إن تقديم تقنيات التصوير المساحي لن يساعد فقط في الحفاظ على القطع المفقودة، بل سيقلل أيضًا من الحدود بين الأجيال المختلفة وتراثها. علاوة على ذلك، يمكن أن يساعد الواقع الافتراضي والواقع المعزز المتاحف في جذب جماهير جديدة وتشجيع الزيارات المتكررة من المتاحف الحالية. بالإضافة إلى ذلك، يمكن لهذه التقنيات أن تساعد المتاحف في الوصول إلى جمهور أوسع من خلال توفير جولات ومعارض افتراضية يمكن الوصول إليها من أي مكان في العالم، مما يسهل على الأشخاص التفاعل مع الفن والثقافة بغض النظر عن موقعهم.

الكلمات المفتاحية: *التراث الافتراضى، المسح التصويرى، الواقع الافتراضى، الواقع المعزز، تفاعل المستخدم.*

1.Introduction

Egypt has a rich and diverse cultural heritage but is most well-known for its ancient pyramids and temples. Many ancient Egyptian artifacts have been transferred and displayed in museums around the world, often without proper documentation or consent. Currently, Egypt is working to bring these artifacts back, including the Rosetta Stone which was discovered by Napoleon's army and later surrendered to the British. The primary objective of a capstone project is to address the historical circumstances surrounding the transfer of Egypt's cultural treasures and their ongoing display in museums (Anna, 2018). Moreover, The COVID-19 pandemic has had a global impact on the tourism industry, including museums. This has caused significant upheaval in the cultural heritage sector as well (Neel, Shurvo, 2020).

Therefore, to protect historical artifacts, documentation can be one of the necessary for preserving accurate and precise results. photogrammetry is one of the documentation tools which it is a technique that involves taking multiple photographs of an object or building from different angles and using software to create a 3D model. This method is particularly useful for documenting historical artifacts because it allows for detailed and accurate representations of the object without the need for physical contact. Besides, it is used effectively in cultural heritage to produce 3D models of historical buildings and artifacts (Uslu and Uysal, 2017; Uslu et. al, 2016; Zeybek and Kaya, 2020). Utilizing virtual reality (VR) and augmented reality (AR) as tools for user interaction can indeed enhance the experience of exploring Egyptian artifacts and provide a unique way to engage with cultural heritage which is the focus of this research. VR can create immersive environments where users can virtually visit museums, while AR can overlay digital information onto the real world, allowing users to interact with virtual artifacts in their physical surroundings. The paper aims to increase awareness by assessing user interaction with unattainable artifacts, specifically the Rosetta Stone, using Photogrammetry. The method used Recap Autodesk software to generate an accurate 3D model of the Rosetta Stone, which was then uploaded onto 3D Vista software and the Vuforia Unity plugin for virtual and augmented user interaction. A survey was conducted to test the model and assess their interaction.

2. Literature Review

2.1. ADVANCED TECHNOLOGIES FOR DOCUMENTATION

The preservation of historical artifacts using advanced 3D measurement technologies becomes an efficient tool for documentation. Multiple techniques are available for the documentation and restoration of historical structures. Imaging-based modeling and Range-based modeling are increasingly becoming popular techniques because of their comprehensive, precise, and efficient attributes (Arnadi and Pierre, 2017). Different types of photogrammetry are employed based on the characteristics of the object being modeled. The main classification is determined by whether the photographs are captured from an aerial perspective or from a ground perspective. Aerial photogrammetry involves using satellite or airplane images to show terrain, while terrestrial photogrammetry uses images that are taken from a spot close to the ground (Klaus and pierre 2002). A study done by (R.A et al., 2016) shows a model of the tea house that had been done by terrestrial laser scanning method and terrestrial photogrammetric method. The building was restored as a teahouse in the garden of the pavilion during the conversion. Approximately 8.5 meters of the study area were photographed, resulting in a collection of 36 images. From these images, 12 were chosen for the creation of 3D models using photogrammetry. The software utilized for this process was Photo Modeler, developed by Eos System. A Samsung Camera with a resolution of 5 MP, which is a non-metric camera, was employed. To ensure accuracy, points necessary for generating the 3D model were marked in at least three of the pictures. This approach proved effective in increasing the precision of the model. Finally, a 3D drawing was created by vectorizing a specific detail from one of the three photos, and the drawing was completed using a total of 12 photos. Another example that used photogrammetry is Cimcime Sultan Tomb which is located at the Erzurum city of Turkey. The tomb was modeled in two separate perspectives: aerial and ground, using DSLR camera for ground photographs, while Phantom 3 Pro UAV was used for aerial shots with various angles and distances. During photographing, the sun angle was taken into consideration. Agisoft software was to generate the 3D model from the images. The procedure of "tying" and "orienting" the photos with each other (Align procedure) was initially carried out in the 3D model. A "dense point cloud" was constructed after the "tie point" was constructed. Finally, the mesh and the 3D model were created (Kabadayı et al., 2020).

2.2. USER EXPERIENCE NAVIGATION.

The integration of technology in museums has played a crucial role in increasing the visitor's interactive experiences within museums. Initially, the primary digital technology used was web pages, allowing visitors to information such as pictures and descriptions from the museum's website. However, with the progression of time, technologies as (VR), (AR), and (MR) have become fundamental in creating interactive virtual exhibitions offering immersive and interactive experiences that engage visitors in new ways. These types of technologies offer an immersive experience that enables users to view the physical world while simultaneously overlaying virtual objects onto it and provide multi-perception capabilities that open numerous new possibilities for museum exhibitions and increase the number of online visitors, although the concerns of the museums about the impact on physical visits. (Ning, Qing et al, 2021). Another benefit of using VR and AR in museums is to enhance the user experience by enabling smooth navigation within the museum and integrating images and videos by providing them through a mobile application. To address this concern, studies are being conducted to evaluate visitor behavior on museum websites. The findings suggest that a good website can increase the desire to physically visit the museum. Marty's study of 9 virtual museum websites supports the idea that physical and online visits complement each other. This idea is also supported by Thom-Santelli et al.'s research on the influence of handheld museum guides on visitor navigation (Katerina,2017).
According to Azuma (2011), AR enables users to view the physical world while simultaneously overlaying virtual objects onto it. However, instead of replacing reality, AR enhances and complements it. The ideal experience is for users to perceive a unified space where both real and virtual objects coexist. Immersive environments in VR help to overcome these concerns by allowing visitors to perceive virtual images of artifacts as genuine and enjoyably gather information about collections (Jung et al., 2016). According for what was mentioned, the study created a virtual museum application called V-Museum, which combines augmented and virtual realities with 3D modeling to enhance cultural tourism in Fez, Morocco. The application is designed for mobile devices and allows users to open a virtual door using AR,

which serves as a portal to a fully virtual museum showcasing the city's famous artifacts and historical objects in 3D. The study aimed to evaluate the usability of V-Museum and its contribution to the visit, and data was collected using questionnaires with fifty volunteers ranging between 18 and 50 years old, with twenty having already visited the Medina of Fez and thirty who had not. The study found that V-Museum provided tourists with a general vision of Fez's cultural heritage and encouraged them to visit The implantation of augmented and virtual realities will offer visitors an almost real-life experience of the city (Mohamed et al. 2020). Other advanced 3D measurement technologies such as imaging-based modelling and range-based modelling, has proven to be an efficient tool for the preservation and documentation of historical artifacts. Accordingly, the advancement of museum exhibition technology, particularly in the form of (VR), (AR), and (MR), has revolutionized the way visitors engage with museum exhibits.

According to the literature, it can be concluded, that photogrammetry is a powerful technique that enables the creation of 3D models of objects using photographs taken from different perspectives. There are two main classifications of photogrammetry: aerial photogrammetry and terrestrial photogrammetry. In the context of missing artifacts, Terrestrial photogrammetry can be used to create an accurate 3D model of the object.

To achieve this, the research highlighted specific procedures that should be followed to document an artifact; first, photographs should be taken using a digital camera from various angles and distances to cover the entire monument, taking into consideration the angle of the sun's arrival. Second, the images should be transformed into a 3D model using photogrammetry software. The "tying" and "orienting" of photos with each other (Align procedure) is initially should be carried out in the 3D model. Third, a "dense point cloud" needs to be created, and finally, the mesh and the 3D model will be generated. This process can be a valuable tool in the recovery of looted or missing artifacts, providing a detailed and accurate representation of the object for identification and potential Consequently, Terrestrial photogrammetry approach is deployed in this research paper, guided by the aforementioned explained technique. Additionally, VR and AR have played a significant role in the development of interactive experiences within museums. These technologies offer an immersive experience that enables users to view the physical world while simultaneously overlaying virtual objects onto it. Using these techniques in museums would enhance the user experience by enabling smooth navigation within the museum and integrating images and videos by providing them through a mobile application. That is why both techniques are utilized in this proposed research paper and will be discussed more in the next section.

3.Methods

3.1 STUDY AREA AND TOOLS

The paper aims to focus on utilizing VR and AR to create an interactive and immersive visualization experience by ascertaining the user level of satisfaction and determining the significance of photogrammetry techniques in documenting purloined artifacts. Three main phases were followed; 1) for VR, 3d Vista software was used to create an immersive virtual tour by creating different panorama, to help users to navigate and interact easily. 2) For AR, Vuforia unity plugin software was used through mobile devices, to create artifacts in different environments. Finally, an assessment survey was conducted to measure user satisfaction and gather data on the user experience of VR and AR experiments.

The study was conducted at the Egyptian Museum in Cairo located in the Tahrir Square. This museum is considered one of the oldest archaeological museums in the Middle East which includes the world's greatest collection of Ancient Egyptian antiquities.

During the fieldwork, a set of photographs were collected using a close range technique with a DSLR Nikon D5300 camera for preparing the photogrammetry. Photos were taken at various angles and distances to cover the entire artifacts considering overlapping during the capturing process at 180° and 360° (Figure 1). The angle of both sunlight and artificial light were considered to avoid damaging the object or casting a shadow.

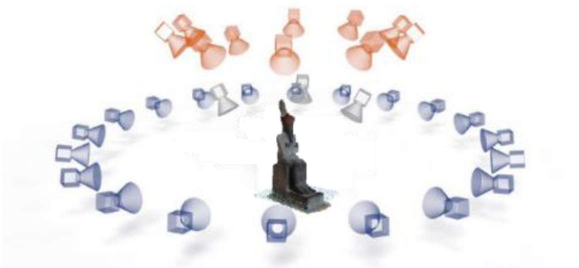

Figure 1. Photogrammetry capture technique.

3.2 METHOD

The method followed in the paper is divided into three main phases: documentation, representation, and dissemination as shown in (figure 2)

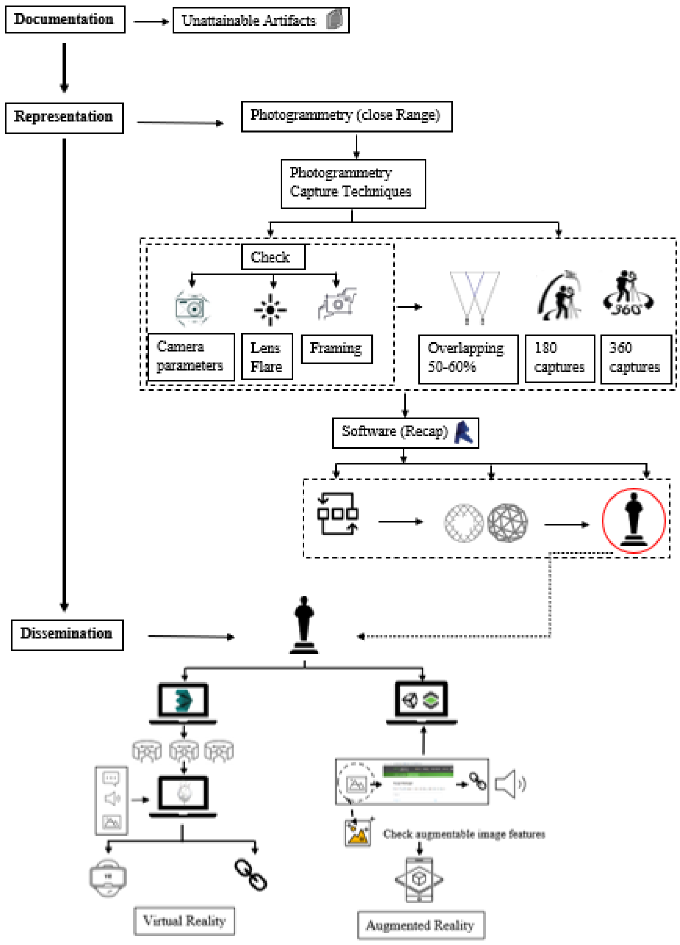

Figure 2. The method workflow

3.2.1. Documentation

In this phase, the data and information were gathered through various ways such as photography, scanning, and survey. This involved capturing images of real-world objects, environments, or artifacts from different angles and perspectives. The steps followed for documentation are:

1. Analyzing the monument site: to understand its historical and cultural significance.
2. Selecting suitable monuments: which was the Rosetta Stone in our case.
3. Capturing images: High-resolution photographs of the selected artifacts are taken from various angles to create an accurate 3D model using cameras or scanners.

4. Sorting images: Only the best images that provide clear and detailed information are chosen for further processing.

3.2.2. Representation (Guidelines for creating accurate 3D model)

After completing the documentation phase, the collected data was processed and transformed into a digital representation using photogrammetry techniques. Photogrammetry involves analyzing and stitching together multiple images to create accurate 3D models. Recap Auto-desk software was used to form a detailed 3D model for navigation. While in the 3D model, the process of "tie" and "orientation" the images with each other was executed followed by creating a dense point cloud. In the end, these point clouds were converted to mesh to identify and correct flaws such as polygon intersections, holes, and double surfaces. The result of this transformation from point cloud to mesh surfaces was generated by an accurate three-dimensional model. Eventually, it was uploaded on sketch fab web for online 3D model navigation (figure 3). A link for representing an accurate 3D model (https://skfb.ly/onIrF)

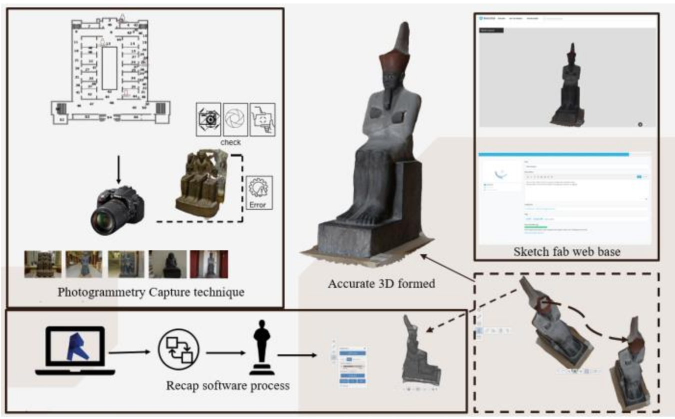

Figure 3. Guidelines using photogrammetry.

3.2.3. Dissemination

The final phase involved sharing and distributing the created visualizations to the intended audience. VR software (3D Vista) is used to create an immersive virtual tour by combining different panoramas. This allows users to navigate and interact with the virtual environment easily. Augmented reality, specifically using the Vuforia Unity plugin software, is employed to overlay virtual artifacts onto real-world environments. This enables users to view and interact with virtual content through their mobile devices. The combination of virtual reality and augmented reality enhances the overall visualization experience and provides users with a more engaging and interactive way to explore documented objects or environments.

3.2.3.1 Virtual reality experiences through panoramic views

Three different panoramic shots were taken. The first was in the entry of the Egyptian museum model, the second was the Rosetta stone model. Those two panoramic shots were taken by uploading the 3D model for both the museum and Rosetta Stone which was done in sketch fab according to photogrammetry techniques. Finally, the third panoramic shot was taken to the Egyptian museum through Samsung Note 20 ultra for high camera resolution by using a photo sphere through the google street application. Therefore, after creating all those panoramas, 3D vista software was used for virtual tour creation. Arrows were added for navigation from different panorama to another. Two options were available where the tour can be done through head-mounted display or downloaded from the hosting for offline mode as shown in (figure 4). A link for a virtual tour of the Egyptian Museum, accessible through the link (https://storage.net-fs.com/hosting/7930058/0/index.htm)

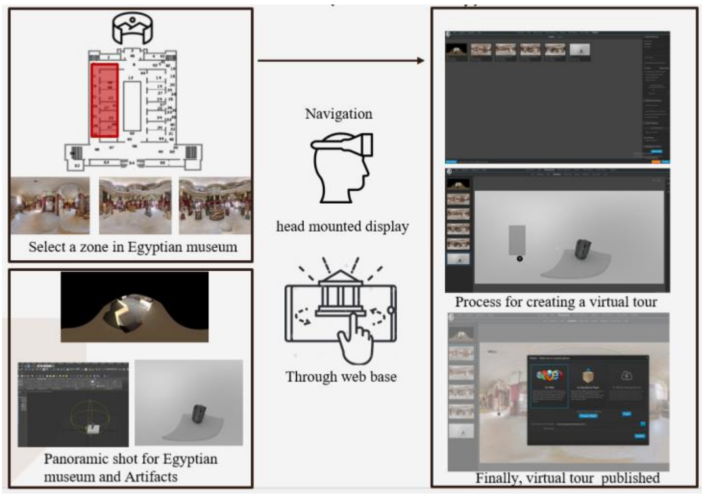

Figure 4. The process of creating the Virtual tour.

3.2.3.2 Augmented Reality experience through a mobile device

For inserting and incorporating Rosetta Stone into an AR experience, the model was uploaded from Sketch fab using photogrammetry techniques. To enable mobile augmented reality, the Vuforia Unity plugin was utilized. This software development kit (SDK) allows for the creation of augmented reality applications that can recognize and track planar images. The process began by selecting a target planar image, which was then uploaded to the Vuforia engine portal. Subsequently, the image target link was generated and uploaded onto the Vuforia Unity plugin. Additionally, a voice-over was added to provide explanations and illustrations of the Rosetta stone model and its accompanying artifacts. When the mobile device's camera detects the image target, the Rosetta stone is automatically displayed where the visitor can view the Rosetta stone in an alternative environment, as depicted in Figure 5.

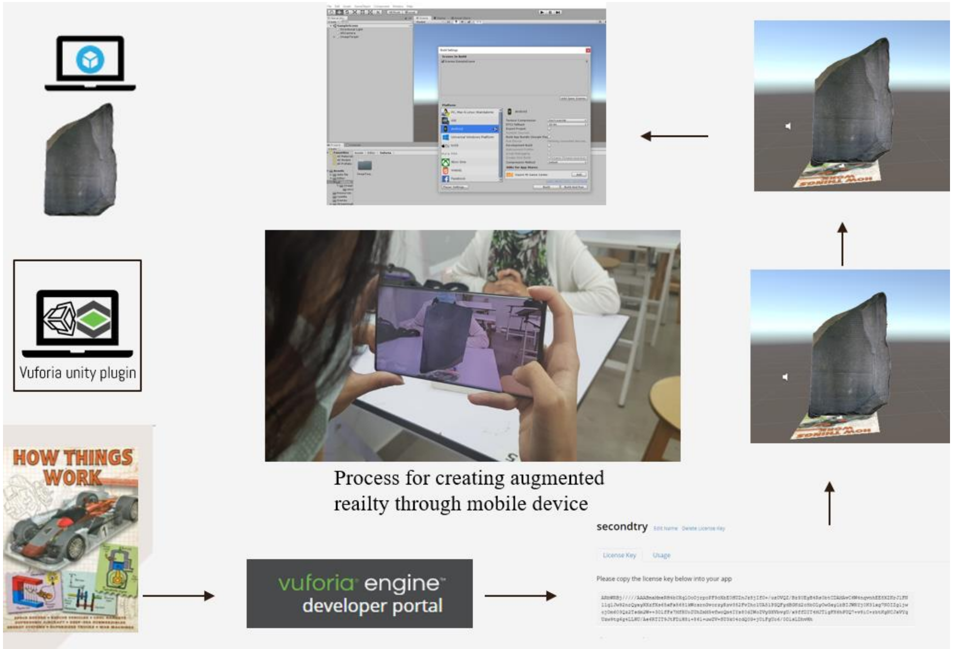

Figure 5: The process of navigating around artifact through augmented reality.

4.Results

The results of the questionnaire showed around thirty-six volunteers who participated in this experience. They are divided into expert, architects, and visitors. The participants were categorized into two groups based on their ages: one group between 20 to 40, and the other group between 40 to 60 years old. The latter group consists of individuals who may not be familiar with technology due to their age. In the first phase, the questions were initially added to measure the frequency of users' visits to museums in general, test their knowledge about Egyptian monuments, and determine if they are aware of our artifacts. Additionally, we aimed to examine their awareness of looted artifacts, such as the Rosetta Stone, and assess how strongly they feel about its return to its original place.

A question was posed to determine the frequency of users' visits to museums, and the results indicate that approximately 68.6% of users visited museums only once a year, indicating that their museum visits were infrequent. Figure 6 illustrates that most respondents on the scale chart prefer the number 3, indicating that 51.4% of users are familiar with Egyptian artifacts. The level of familiarity of users with the Rosetta Stone was measured through a question, revealing that approximately 72.2% of users demonstrated awareness of the Rosetta Stone, while 28% didn't know anything about it where here comes the necessity of raising awareness of our artifacts located outside Egypt. Based on this data, figure 7 shows a tendency towards the number 5 on the scale chart, indicating that 75% of users desire for the Egyptian artifact to be returned to its original location. Conversely, a minority of users (25%) indicated their refusal towards this proposition. Unfortunately, numerous monuments in Egypt have not been adequately preserved and valued, despite their cultural significance. In contrast, other countries have taken measures to ensure the proper preservation and placement of such monuments in esteemed locations. This question aims to assess the willingness of users to return artifacts. Moreover, VR and AR can provide various benefits even if the monuments remain in their original location. These technologies can enhance the experience by adding videos, voiceovers, and images for more detailed descriptions. and this can help users become more fully immersed in the experience.

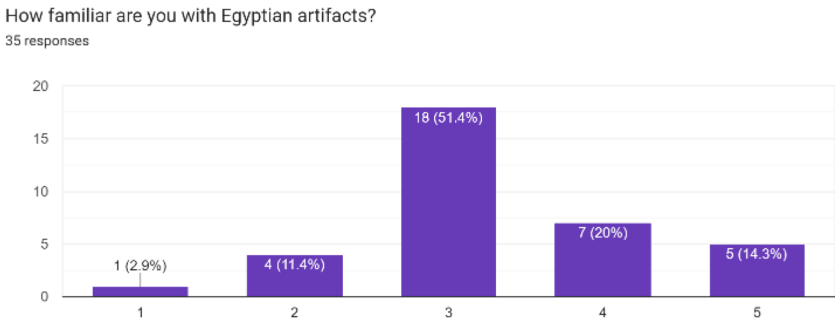

Figure 6: Percentages of respondents to their familiarity towards Egyptian artifacts.

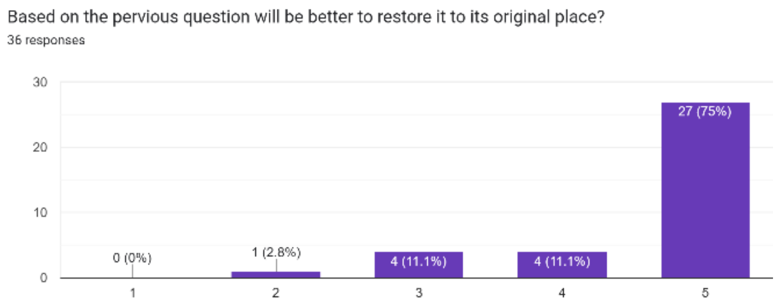

Figure 7: Percentage of respondents to restore the stone back to its original place.

Based on the findings from the initial survey phase, we proceeded with a second phase to evaluate user interaction with the technology employed in creating guidelines for documenting and presenting our artifacts. The primary objective was to develop an accurate 3D model and measure user satisfaction with navigating through it. To facilitate this assessment, we included a link in the survey that directed users to engage with the experience and commence navigation. To ascertain how easily users could identify and navigate the 3D model, we began by asking if they had any prior exposure to a virtual museum and if they had previous experience with virtual reality and augmented reality technologies. It was found that 77.8% of the participants had tried VR and AR before. Based on their responses, we provided a link for users to explore the navigation of the virtual Egyptian museum and assess their overall experience. As part of this experiment, we showcased one of the looted artifacts, namely the Rosetta stone. Moreover, user experience was evaluated by conducting an experiment in which participants navigated around the Rosetta Stone in its original location using augmented reality.

The survey revealed that 91.7% of users highly appreciate the implementation of photogrammetry techniques in documenting artifacts. A link was added for the user to test their level of satisfaction through navigation surround artifacts that approximately rate of 74.3%. This concludes users can navigate and easily identify artifacts. This innovative approach has proven to be an excellent and effective method for capturing detailed and accurate representations of archaeological objects. 69.4% of the users are familiar with virtual museums and 77.8% tried VR and AR before. Moreover, a virtual tour of the Egyptian Museum was introduced, and an overwhelming majority of 94.4% of participants found it to be an excellent method for virtually visiting the museum during the pandemic. Furthermore, Figure 8 indicates that a link was included to measure user satisfaction while exploring the Rosetta Stone within the Egyptian Museum. The responses received were moderate, with a rating of 3 on the scale, and approximately 37.1% of users expressed satisfaction with the experience.

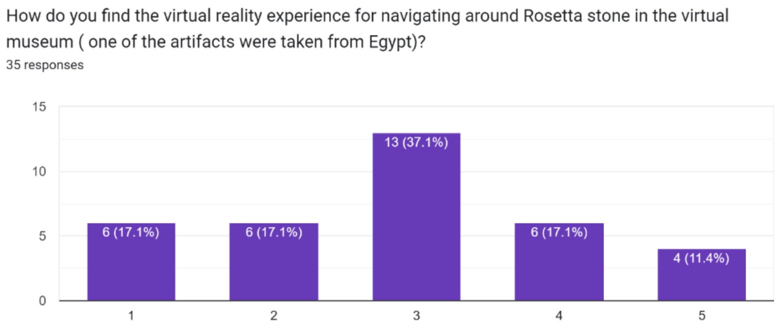

Figure 8: Percentages of respondents to measure user experience in virtual museums.

Figure 9 illustrates an experiment conducted on a user, involving the presentation of an image target for scanning. Subsequently, the Rosetta stone emerged in various environments, prompting participants to express their level of satisfaction. Depicts the responses, with a majority (38.9%) indicating a satisfaction rating of 4 on the scale. While 28 % of the users were not satisfied with the experience which was almost the elder people. This shows that users with young ages were enjoying this virtual representation more.

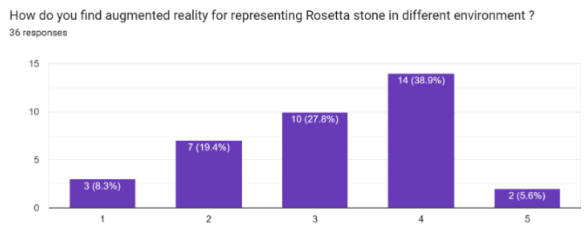

Figure 9: The respondents to their familiarity towards representing Rosetta stone in different environments.

This application, which was created using 3D Vista, allows the user to experience fully immersive navigation inside a virtual museum featuring the Rosetta Stone. Furthermore, the use of Vuforia in mobile devices allows users to evolve in the real world by discovering the Rosetta Stone through an AM application.
In summary, the survey respondents had mixed reactions when trying both virtual reality and augmented reality experiments to present the Rosetta Stone. This led to two different opportunities for different experts. The first expert suggested representing the Rosetta Stone in the Egyptian museum with a focus on user interaction through virtual means, even though the actual stone is housed in the British museum and people appreciate experiencing it in its physical form abroad. On the contrary, another expert argued that using virtual reality and augmented reality to present the Rosetta Stone is an effective approach. They compared it to the psychological phenomenon known as phantom limb pain, where individuals experience pain or discomfort in a limb that has been amputated or no longer exists. By employing visualization techniques, users can simulate the original presence of the Rosetta Stone in its original location, despite it being physically located elsewhere, such as in the British Museum. The main objective of this approach is to increase awareness among different generations and highlight the importance of preserving cultural heritage.

5. Limitations and challenges

The lighting conditions in Egyptian museums were not ideal for taking photos of certain artifacts. While attempting to capture a panoramic shot of the museum, an error occurred due to the limited quality of the mobile camera. As a result, many details were missing from the panorama, and it did not capture a full 360 degrees. To address this issue, the Google Street View application was used to capture a better panorama. However, the process took longer than expected due to the crowdedness of the museum. Additionally, the Vuforia program platform needs to be unified across operating systems used on laptops and mobile phones. For example, a Mac laptop with an iPhone and a normal laptop with a Windows operating system with an Android phone. To create an AR platform, the iOS mobile device used for capturing images needed to be changed to an Android mobile device.

6. Ethical and Legal implications

According to Civilization Rights Institute (2023), by Rashed, one of the initiatives by this institute is to repatriate looted artifacts to their origin places. It is the entitlement of every country to claim both the material and moral ownership of their cultural and civilization heritage against any individual or entity that directly or indirectly exploits or benefits from it, including through images, replicas, imitations, names, slogans, or any other means. The objective of restoring these claims is to safeguard and maintain the civilization heritage in their original homeland to prevent their extinction. Therefore, this research highlights the importance of retrieving purloined artifacts by aiding their visualization in their original habitat. Further research about the ethical and legal implications of the looted artifacts in museums needed to be studied due to the negotiating of many countries to return back these artifacts as highlighted in (Elia, 2009).

7. Conclusion

The work consists of documenting the purloined artifacts to raise awareness using photogrammetry techniques. It also involves developing a virtual museum application through a combination of virtual reality and augmented reality to enrich the user experience and increase awareness of our Egyptian heritage. Moreover, considering the COVID-19 pandemic and other potential global challenges, Virtual Museums are proving to be an exceptional resource to enhance its historical culture virtually if there are no access to the heritage sites.

The research focused on two main issues, the demand by Egypt to return unattainable artifacts and the impact of the COVID-19 pandemic on museum closures worldwide. To address these challenges, a guideline was developed for documenting and representing unattainable artifacts using photogrammetry techniques to create accurate 3D models. Additionally, the study explored how VR and AR can be used to disseminate these artifacts. In this research, software applications were utilized for the documentation and representation of unattainable artifacts. Additionally, the 3D Vista software was employed for creating virtual tours, while the Vuforia Unity plugin was used for augmented reality purposes.

The research also examined the potential impact of these techniques on user experience. Two different user feedbacks were observed, the first was that some of the users did not find any satisfaction in interacting around the Rosetta stone virtually while the original one is presented in the British Museum. Unlike the majority, they found it a very interesting experience to feel the missing artifacts of its original place. Therefore, this raised their awareness to call for their civilization rights.

Further research suggested to construct a complete space within the Egyptian museums that brings together all the looted artifacts from various countries abroad to be exhibited within their real context. This will enhance our system by incorporating innovative approaches for interaction with a wider range of objects. Additionally, it will facilitate seamless interactions among these objects through integration. Additionally, more mobile apps can be integrated for user-friendly through scanning the objects allowing for fully immersion in the journey of these artifacts to facilitate interaction in mixed reality applications.

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A METHOD PROPOSAL FOR 3D DIGITAL MODELLING OF HISTORICAL OTTOMAN FOUNTAINS

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Abstract. Historical buildings are in critical position in terms of heritage value with their role in examination and preservation of urban culture and identity. Historical buildings are affected by changes in physical and social environment. Consequently, they face risks such as deformation and destruction. Considering that documentation of historical buildings provides contributions to research, conservation and restoration studies. Fountains, public elements of Ottoman civil architecture, hold significant positions in cultural and architectural heritage. Creation of 3D digital models of Ottoman fountains will also make significant contributions to studies. This study aims to search for method for 3D digital modelling of Ottoman fountains through example of III. Ahmed Fountain. Ottoman fountains contain common characteristics and typological elements coming from construction period, location and architectural style. This study presents modelling method combines multiple techniques for 3D digital modelling of fountains, due to inadequacy of single modelling method in conveying details, and applicability of chosen method to digital modelling process of fountains with different characteristics. In this study, research was carried out on different modelling methods to create most detailed and accurate model. Fountain elements are classified into three subgroups as main mass, details and regular elements to apply most appropriate modelling methods. Main mass was shaped on Rhinoceros using geometry-based modelling method, while ornaments in regular elements group were created in Grasshopper with parametric modelling. Detail elements were created in Agisoft Metashape with photogrammetric modelling to convey in detail. This study presents gradual method proposal with multiple techniques but also tries to include suggestions for problems encountered in modelling process of historical buildings. In this context, texture and geometry deformations in scanning models were corrected with ZBrush, and color differences caused by effect of light and shadow were tried to be solved by creating new texture maps on Adobe Substance 3D Sampler.

A METHOD PROPOSAL FOR 3D DIGITAL MODELING OF HISTORICAL OTTOMAN FOUNTAINS

Keywords: *Ottoman fountains, Cultural heritage, 3D modelling, Photogrammetry, Parametric modelling.*

ملخص. تحتل المباني التاريخية مكانة عظيمة من حيث قيمة التراث بالإضافة لدورها المهم في استيعاب وتقييم الثقافة والهوية الحضرية والحفاظ عليها. تتأثر المباني التاريخية بالتغيرات في البيئة المادية والاجتماعية وبالتالي تواجه مخاطر مثل التشوه والدمار مع إدراك أن توثيق المباني التاريخية يقدم مساهمات في دراسات البحث والحفاظ والترميم. تحتل النوافير التي تعتبر عناصر عامة من العمارة المدنية العثمانية مناصب مهمة في التراث الثقافي والمعماري لذلك سيساهم إنشاء مجسمات رقمية ثلاثية الأبعاد للنوافير العثمانية بشكل كبير في الدراسات. تهدف هذه الدراسة إلى البحث عن طريقة لتشكيل مجسمات رقمية ثلاثية الأبعاد للنوافير العثمانية من خلال مثال نافورة أحمد الثالثة. تحتوي النوافير العثمانية على خصائص مشتركة وعناصر نمطية تعود إلى فترة البناء والموقع والأسلوب المعماري. تقدم هذه الدراسة لتشكيل المجسمات طريقة تجمع بين تقنيات متعددة للتشكيل الرقمي ثلاثي الأبعاد للنوافير بسبب عدم كفاية طريقة تشكيل فردية في نقل التفاصيل مع إمكانية تطبيق الطريقة المختارة على عملية التشكيل الرقمي للنوافير ذات الخصائص المختلفة. في هذه الدراسة، تم إجراء البحث على طرق مختلفة لإنشاء مجسم أكثر تفصيلاً ودقة. يتم تصنيف عناصر النافورة إلى ثلاث مجموعات فرعية والتي هي كتلة رئيسية وعناصر تفصيلية وعناصر منتظمة لاكتشاف أساليب التشكيل الأنسب لكل حالة. تم تشكيل الكتلة الرئيسية عبر برنامج Rhinoceros باستخدام طريقة التشكيل الهندسبة بينما تم إنشاء الزخاريف في مجموعة العناصر العادية عبر برنامج Grasshopper اعتمادا على التشكيل البارامتري ثم تمت عملية التدقيق في العناصر التفصيلية عبر برنامج Agisoft Metashape من خلال تقنية المسح الفوتوغرافي للحصول على أدق التفاصيل. تقدم هذه الدراسة عرض اقتراحي لطريقة تدريجية بتقنيات متعددة وتتضمن اقتراحات لحل المشاكل التي تمت مواجهتها أثناء تشكيل مجسمات المباني التاريخية. في هذا السياق، استخدم برنامج ZBrush لتصحيح الأخطاء التي تسببت ببعض التحريف في الشكل الهندسي للمجسمات بعد المسح التصويري، وتم حل اختلافات الألوان الناتجة عن تأثير الضوء والظل من خلال إنشاء خرائط نسيج جديدة على Adobe Substance 3D Sampler.

الكلمات الرئيسية: *النوافير العثمانية، التراث الثقافي، المجسمات ثلاثية الأبعاد، القياس التصويري، المجسمات البارامترية.*

1. Introduction

Historical buildings are information carriers for civilization history as witnesses of social processes. Historical buildings contain information about social, cultural, architectural history of societies. Due to these features, historical buildings are study object of disciplines. Historical buildings are also affected by social and physical processes. These structures, which undergo physical deformation, lose functions and become out of use with developments. Due to such situations, preservation and documentation of historical structures has great importance.

In documentation of historical buildings, 2D drawings and photographing are often preferred methods. With development of technology, studies are also carried out to create 3D digital models for documentation of historical buildings. Documenting historical buildings with 2D/3D documentation methods provides contributions to research, conservation and restoration.

2. Istanbul, Water and Fountains

In formation process of historical buildings, forms and functions have been shaped in line with needs of society, and have been diversified by being influenced by social processes. One of the examples where effects can be seen in diversity of historical buildings is Istanbul and water structures. Contrary to advantages of location and natural riches, Istanbul has not been rich in drinking water throughout history (Aynur and Karateke, 2022). For this reason, meeting water needs and delivering water were critical for both Byzantine and Ottoman. Collecting rainwater and transporting water from sources are important methods used in water supply (Aynur and Karateke, 2022). Process of transporting water and distributing to users also affected social, cultural and economic life, and brought along architectural units and business. During Ottoman period, there was profession called Saka sold water to houses and provided transportation on foot or horseback (Aynur and Karateke, 2022).

Water issue has also had effects on city's architecture for centuries, and architectural structures created for water supply and distribution purpose have taken critical place. Valens Aqueduct, built in 4th century, is waterway to bring water to city, while Basilica Cistern, built in 6th century, is water reservoir built to collect rainwater. These structures still maintain their existence and contain important information about history. During Ottoman period, water supply and distribution network was developed and new architectural structures began to take place. A significant example of these architectural structures is fountains. Since water carried to city by arches, pipes and channels is valuable resource, it was transferred to sheltered structure in order not to waste it and this structure was named as fountain (Özer, 2008). As city developed physically and demographically, new waterways and street fountains were built (Aynur and Karateke, 2022).

Fountains were built by wealthy people to earn charity, by rulers as sign of power and innovation (Yeler and Yeler, 2021). Fountains, which are public gathering areas, have also taken place in social life as communication center of society (Sağır, 2016). Fountains had impact on neighborhood formations of Ottoman city, and differences in typologies and architectural styles were observed along with time. Fountain structures shed light on wide variety of issues such as urban design and planning, social and cultural life as well as architectural knowledge. With development of water distribution network in today and every household's access to drinking water, fountains have lost their function of distributing water and many of fountains have been out of use. Disasters such as earthquakes, fires and human interventions pose risk of physical deformation and destruction of fountains.

Among historical buildings, fountains, which are relatively small-scale examples of architecture, are cultural heritage treasures that offer information in wide variety of areas. Architectural and typological forms, together with heritage value they contain, make Ottoman fountains important and worth examining within the scope of this study. It is thought digital models of fountains that are desired to be created with method proposal to be created for digital modeling of historical Ottoman fountains will make contributions to research studies from different disciplines. It is aimed 3D digital models to be created will also contribute to conservation and restoration works of fountains face risk of physical deformation and destruction.

3. Documentation and Modeling of Historical Buildings

Historical buildings are faced with risks of losing functions, acquiring new functions and being out of use with changes. In addition, these buildings are faced with natural threats such as earthquakes and fire, and man-made threats such as war, theft and vandalism (Oktay, Taş and Taş, 2020). These threats also bring about destructions disrupt structural integrity of buildings. Due to risk of deformation and destruction, maintenance and protection of historical buildings are of critical importance. One of main purposes of preserving historical monuments is to preserve their document value and structural integrity without losing their original features and to transfer value and integrity to future generations (Örmecioğlu, 2010). In this context, historical building documentation is of great importance in terms of recording original qualities of works and creating resources for conservation, repair and restoration works to be carried out.

It is possible to document using 2D and 3D methods in documentation of historical buildings. Measured surveys and photographing are commonly used methods during documentation in 2-dimensions. After processing data collected with measurement and photographing, 2D documents are obtained by creating drawings of building. In this process, drawings produced by processing data can be created in physical environment as well as in digital environment.

Documents created with 3D documentation methods contribute significantly to archiving of historical building, conservation and restoration studies. In addition, incorporating 3D digital models produced in this process into virtual environment in following stages allows these artifacts, which have important place in civilization history, to gain accessible feature for all humanity.

In addition to photographic recording and measured surveys, some methods allow detailed data to be obtained in documentation process in 3-dimensions. Terrestrial laser scanning and photogrammetry are two of these methods. Terrestrial laser scanning is method allows creating 3-dimensional point clusters of objects with angle and length measurements obtained with help of LiDAR (light detection and ranging) (Liang *et al*., 2016). Terrestrial laser scanning has high precision to obtain detailed data even in complex structures and can provide comprehensive data. Since this method does not require physical contact, it is effective tool for measuring sensitive structures can be damaged by physical intervention. In addition to these advantages, difficulty of processing detailed and complex data obtained by terrestrial laser scanning and lack of color and texture information on structures are among disadvantages of method. In addition, need for laser scanning equipment and qualified practitioners in method makes terrestrial laser scanning method costly and has restrictive effect on use of method. Another method used in 3D documentation is photogrammetry. Providing dimensional data of object using photographs of that object is defined as photogrammetry (Mikhail, Bethel and McGlone, 2001). As with terrestrial laser scanning method, photogrammetry method has advantages and disadvantages. Unlike laser scanning, this method, which has advantage of being low-cost in terms of not requiring equipment and practitioners, also allows obtaining color and texture information. Along with advantages, quality of device used in photogrammetry method, number of photos and angles, shadows and reflections formed by light change play role in accuracy of final model and put method in disadvantageous position.

Although accuracy of 3D documentation methods increases with advances and developments in technology, each method has advantages and disadvantages. Due to information and detail richness of historical buildings, use of single method may be insufficient in 3D digital documentation. In this context, this study proposes modeling method that uses multiple technique to reach accurate and detailed model in process of creating digital models of Ottoman fountains.

In previous studies on modeling of historical buildings, inadequacy of single method in 3-dimensional modeling process of historical buildings was mentioned and modeling experiments were carried out by using different methods together. El-Hakim *et al*. (2007) mention inadequacy of using single method in creating detailed models despite development of modeling tools in study titled Detailed 3D Modeling of Castles, in which they work on creation of models of castles in Northern Italy. Unlike previous ones, this study examines digital modeling process of historical buildings through Ottoman fountains, categorizes fountains based on typological and physical elements, and presents method proposal aims to determine and apply modeling method suitable for each category to reach accurate and detailed result model with sub-models created.

4. Digital Modeling of Historical Ottoman Fountains

Fountains have important place in public life of city with their functions and architecture. With demographic and geographical growth of city, number of fountains has increased to deliver water to users, and new terms have emerged according to location, functioning or architectural features of fountains. Sebil can be shown as example of these terms. Sebil is described as buffet where attendant supplies water from behind window bars (Petersen, 1996). These structures, which are fountains where water can be supplied free of charge, are called by special name due to differences in architectural form and water supply provided by officer. This study examines water structures with function of supplying drinking water, which are expressed with special names such as fountain, water kiosk and water fountain, by considering them under main title of fountain.

Ottoman fountains, along with their function of providing water, are also important architectural elements. It is possible to see traces of period in which they were built, builder and owner of work, as in historical buildings. Fountains designed with functional and aesthetic traces are architectural structures with rich level of detail. Increase in detail level is also effective in process of creating three-dimensional digital models of fountains. However, there are also external factors affect modeling of fountains. Use of some fountains, which are out of use today, with different functions can be given as example of external factors. As a result of refunctioning observed especially in fountains, interventions made to fountain affect accuracy of modeling results (Figure 1). However, especially in square fountains, growth of scale makes it difficult to reach some points and creates disadvantage in use of methods such as terrestrial laser scanning. Since fountains are located in public spaces, users around fountain make it difficult to collect healthy data in photo-based methods such as photogrammetry and affect final product. Considering architectural and external factors, this study proposes modeling method formed by use of multiple techniques, with thought using single method in creating three-dimensional digital models of fountains would be inadequate in creating comprehensive and realistic model.

Figure 1. Refunctioning of fountain.

5. Case Study: Digital Modeling of the Fountain of III. Ahmed

III. Ahmed Fountain is fountain located in Üsküdar district of Istanbul. Fountain, which was built by III. Ahmed in 1729 for his mother Emetullah Gülnuş Valide Sultan, was restored in 1932, 1955 and 2000 (Aynur and Karateke, 2022). Fountain has four facades, and on each facade, there are inscriptions containing couplets of historical personalities. Fountain, which is out of use today, takes its place as important elements of square where it is located.

Although each of Ottoman fountains has special characteristics, they also have common morphological features and typological elements with functions and periods (Figure 2). Basin, spout, arch, niche and inscription can be counted among these common typological elements. The study aims to use modeling method suitable for characteristics of typological elements to create accurate digital models of fountains and to reach final model by using multiple method together. III. Ahmed Fountain also incorporates similar typological elements with other fountains. In this context, case study starts with examination of typological elements and modeling methods through III. Ahmed Fountain.

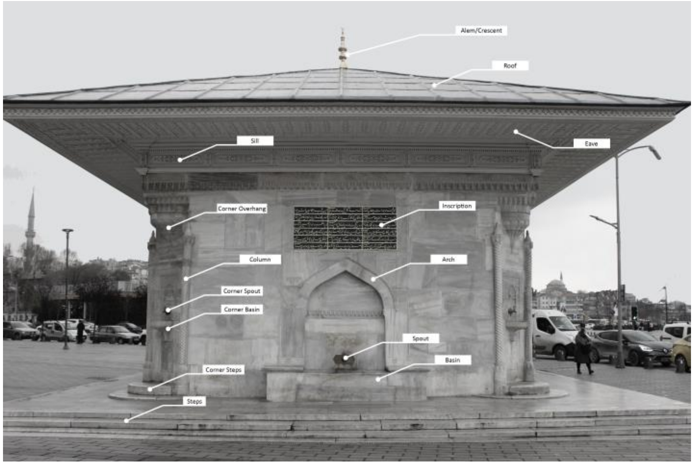


Figure 2. Elements of Ottoman fountain.

5.1. TYPOLOGICAL ELEMENTS OF THE FOUNTAIN OF III. AHMED

III. Ahmed fountain 3D digital modeling study started by examining typological elements of fountain. After examining, modeling methods for elements were investigated. Fountain elements were categorized into three subgroups according to modeling methods to be used (Figure 3). These subgroups are named details, main mass and regular elements.

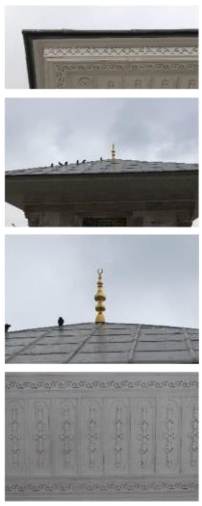
	Main Mass	Details	Regular Elements
Üsküdar III. Ahmed Fountain			

Figure 3. Grouping of III. Ahmed fountain elements.

Detail group includes main and side niches, basins, inscriptions, spouts, corner basins, twisted columns, corner overhangs and corner steps. Elements in group have characteristic features and complex forms compared to other group elements. Since elements are custom-made, elements such as twisted columns and corner fountains are located on four sides of fountain, but each exhibits different characteristic. To convey existing deformations as well as different characteristics, it was decided to use photogrammetry method in detail group.

Main mass group is group expresses mass on which detail and regular elements are located. This group, which is made of marble, especially for III. Ahmed Fountain contains fewer characteristic features compared to detail elements. In modeling main mass, creating model with correct dimensions and determining placement of detail elements on mass were considered critical, and therefore, geometry-based modeling method in Rhinoceros was deemed appropriate for modeling main mass.

Wooden ceiling sill carvings, eaves carvings, roof and crescent are considered under regular elements. Roof and crescent elements contain certain geometric rules. At the same time, wooden ceiling sill and eaves carvings were produced by rules, each replicating unique motif. By examining these rules, use of Grasshopper parametric modeling method was preferred for regular elements group. After formation of groups and decision on modeling methods, data gathering phase started.

5.2. DATA GATHERING

The study uses existing plans and elevation drawings, photographs and measurements as data. Data collection process for III. Ahmed fountain modeling study started with literature review. Historical photographs of fountain and scaled drawings were obtained from sources. After research, site survey was carried out. The whole and detailed elements of fountain were photographed for photogrammetric modeling. Photographing was completed by paying attention to criteria such as light, angle and number of photos. After photographic survey, measured survey stage was started. It is aimed to prevent incomplete and incorrect information by using multiple data collection method.

5.3. MODELING PROCESS

After data-gathering process, 3D digital models of detail, main mass and regular elements groups were created using appropriate modeling methods.

5.3.1. Modeling of Details

Photogrammetry method was used in modeling of detail group, which includes main and side niches, basins, inscriptions, spouts, corner basins, twisted columns, corner overhangs and corner steps. In site survey, data pool was created with general photographs of fountain and separate photographing of details. Then, model creation process of detail elements was started in Agisoft Metashape software. For modeling work in Agisoft Metashape, photos of element to be modeled are imported into program. With align photos command, photos are aligned by software according to shooting angles. After alignment of photo positions, first output of model is obtained by creating dense cloud. Mesh is created from resulting dense cloud. Scanning model is completed by applying texture obtained from photographic data to created mesh model (Figure 4). Factors such as ambient light, angle and quality of photographs affect digital models obtained from photographs, and some structural and textural deformations may occur in model. Pixologic Zbrush sculpting tool was used in study to repair problems in Metashape models and to increase accuracy of model.

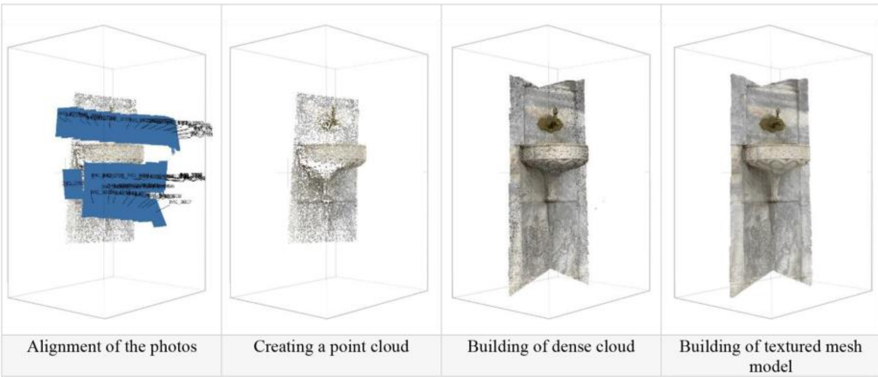
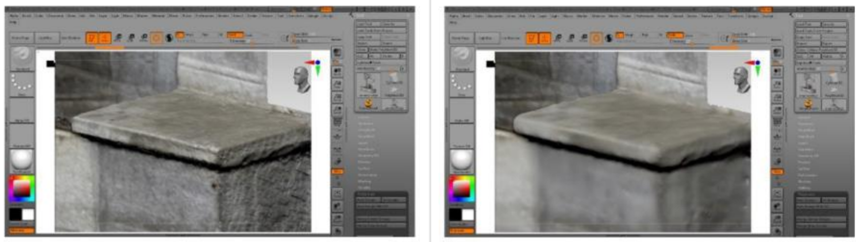


Figure 4. Modeling of details in Agisoft Metashape.

In ZBrush program, structural deformations of scanning models were removed. Deformations such as unmeshed points, gaps and cuts were repaired. Then, texture arrangements were made by material properties of model. In scanning model, texture is shaped and diversified with number of polygons that can be created. For example, element made with marble material may not reflect smooth texture that is characteristic of marble material due to polygon features of scanning model. At this stage, texture adjustments were made with ZBrush to smooth surface and create model close to real (Figure 5).



Texture of the scanning model of the marble seating platform	Edited and softened marble seating platform texture in ZBrush

Figure 5. Texture adjustments in ZBrush.

Modeling process of detail elements was completed with creation of scanning models on Agisoft Metashape with photogrammetry method, and then structural and textural arrangements of scanning models using ZBrush. As can be seen from process, in addition to inadequacy of single method in modeling process of historical buildings, use of single software may also be insufficient to create holistic models. The study sees this need and tries to support modeling process with use of multiple techniques and software.

5.3.2. Modeling of Main Mass

Modeling of main mass on which detail and regular elements are located was carried out on Rhinoceros with geometry-based modeling. Required data for modeling of main mass are scaled drawings and measurement information from site survey. However, there is some information is not included in drawings and cannot be obtained during measurement due to physical insufficiencies. At this stage, scanning model of fountain created by photogrammetry was used to complete missing information. During data collection, total fountain model was created in Agisoft Metashape program, using 360-degree sequential photographs (Figure 6). Main purpose of total model is to provide reference for main mass size and detail placement. For this reason, model consisting of several polygons has been created that will not adversely affect efficiency of device, although it contains required geometric data. With scanning model and measurement data, stepped podium where main mass is located was created. Then façades were modeled and main mass model was completed by creating parts on façade where details would be placed (Figure 7).

Figure 6. Scan model of fountain and plan schema.

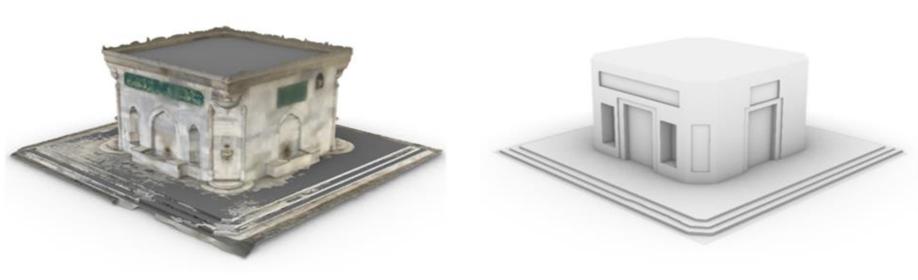


Figure 7. Modeling main mass and places of details with the help of photogrammetric scan model and measurement data.

The study uses modeling methods as total model creation tool in digital model creation, as well as for resource creation. While photogrammetry method is used to create final products in modeling of detail group, same method is used to create data and references in modeling of main mass.

5.3.3. Modeling of Regular Elements

Regular elements group, which includes wooden ceiling sill carvings, eaves carvings, roof and crescent elements, was modeled in Rhinoceros and Grasshopper environments with geometry-based and parametric modeling methods.

Measurements of roof and crescent, which were arranged with restoration works of fountain, are included in scaled elevation drawings. Profile sections for crescent and roof were created in Autocad from elevation drawings and photographic data (Figure 8). Afterwards, these sections were converted into three-dimensional model in Rhinoceros and Grasshopper (Figure 9).

Figure 8. Profile section of crescent.

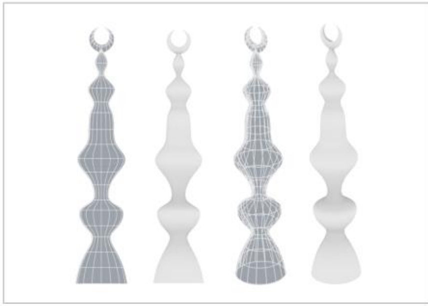


Figure 9. 3D model of crescent.

Wooden ceiling sill and eaves carvings, which are in regular elements group, were created by repetitive reproduction of unique motif. In modeling of these elements, digital drawings of repetitive motifs were produced over appearance drawings and visual data (Figure 10). After modeling motif in Rhinoceros, multiplication algorithm was created over parameters such as number and position in Grasshopper (Figure 11). With production of motif by algorithm, digital models of wooden ceiling sill and eave carvings were reached and modeling of elements belonging to regular elements group was completed (Figure 12, 13).

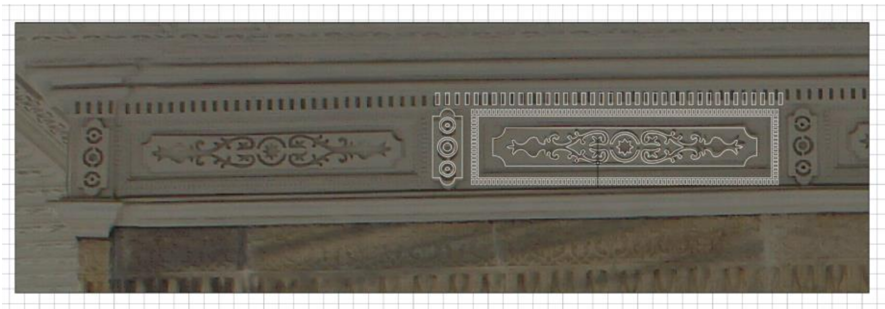


Figure 10. Digital drawing of sill carving motif.

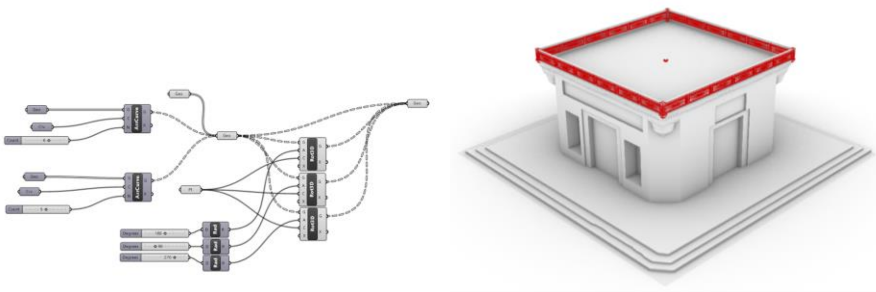


Figure 11. Grasshopper algorithm and multiplication of sill carvings.

Figure 12. Model of wooden sill carvings.

Figure 13. Model of wooden eave carvings.

5.4. INTEGRATION OF THE MODELING GROUPS

After models in detail, main mass and regular elements groups were completed, these models were integrated. First of all, regular elements were added to mass model in Grasshopper. Then, detail models were placed in their determined places on main mass and holistic model of fountain was reached (Figure 14).

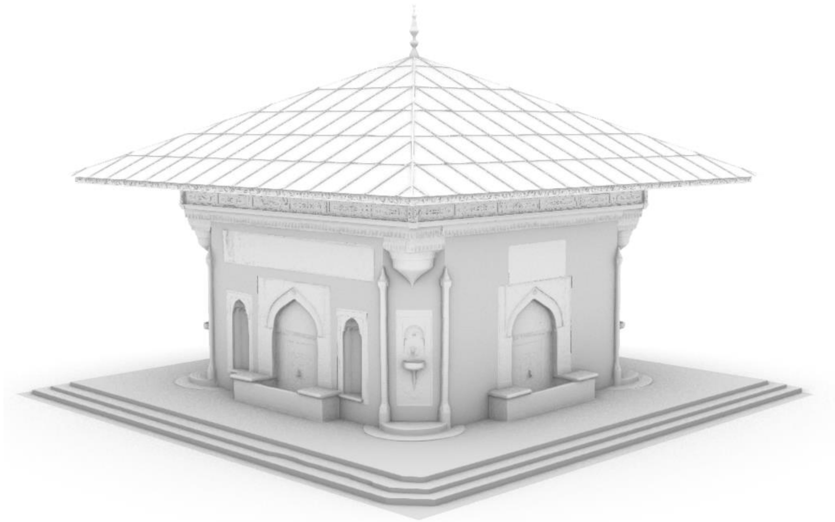


Figure 14. Total model of fountain without texture.

5.5. TEXTURING

After holistic model of III. Ahmed Fountain was created; texture applications were studied for final model. Texture application is shaped as editing existing texture maps and creating new maps needed.

5.5.1. *Editing Existing Texture Maps*

One of advantages of photogrammetric modeling is models created contain color and texture information obtained from photographs. In this way, scan models belonging to detail group created via Agisoft Metashape contain texture maps. However, due to factors such as weather conditions and shooting angle, changes may occur in values such as hue, saturation and brightness in photographs. In order to organize such color differences and to give texture in model correctly, texture maps were improved and edited via Adobe Photoshop and edited texture maps were applied to models.

5.5.2. *Creating New Texture Maps*

Since main mass model uses photogrammetry data as data source and model itself is created with geometry-based modeling in Rhinoceros, texture map is needed. Because facade photographs in existing photographic data are insufficient in terms of light and shadow factors, texture needed was created in Adobe Substance 3D Sampler program, which allows creating 3d material from photographic data.

In this process, sample image to be used in production of texture from facade photographs was selected (Figure 15). Then, by editing parameters such as tile sizes, joint spacing and colors in Adobe Substance 3D Sampler, which is based on this image, material close to visual and physical texture of existing facade and texture map of this material were tried to be created (Figure 16). Created texture map was applied to main mass. With application of texture maps to combined integrated fountain model, final model was reached in study (Figure 17).

Figure 15. Sample from facade.

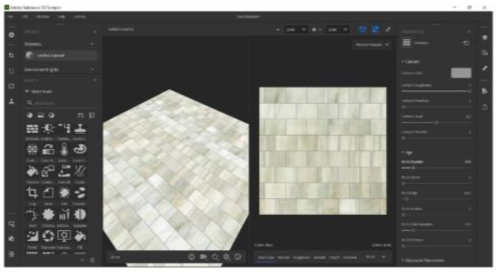


Figure 16. Texture map creation for façade in Adobe 3D Sampler.

Figure 17. Final model of III. Ahmed fountain.

6. Future Works

Method proposal for digital modeling of historical Ottoman fountains created within the scope of study has been studied as case study. Within the scope of case study, it was observed method proposal gave successful result in creation of detailed 3D digital model of III. Ahmed Fountain. For future works, it is aimed to develop method by conducting experiments on applicability of method proposed in study in creating digital models of Ottoman fountains in different periods and architectural styles.

As preliminary to future studies, historical Ottoman fountain and sebil examples from different periods and architectural styles were examined. Typological elements of samples were tried to be categorized under detail, main mass and regular elements groups (Figure 18). This grouping study is aimed to predict applicability of method which presented in this study to create digital models of different fountain samples.

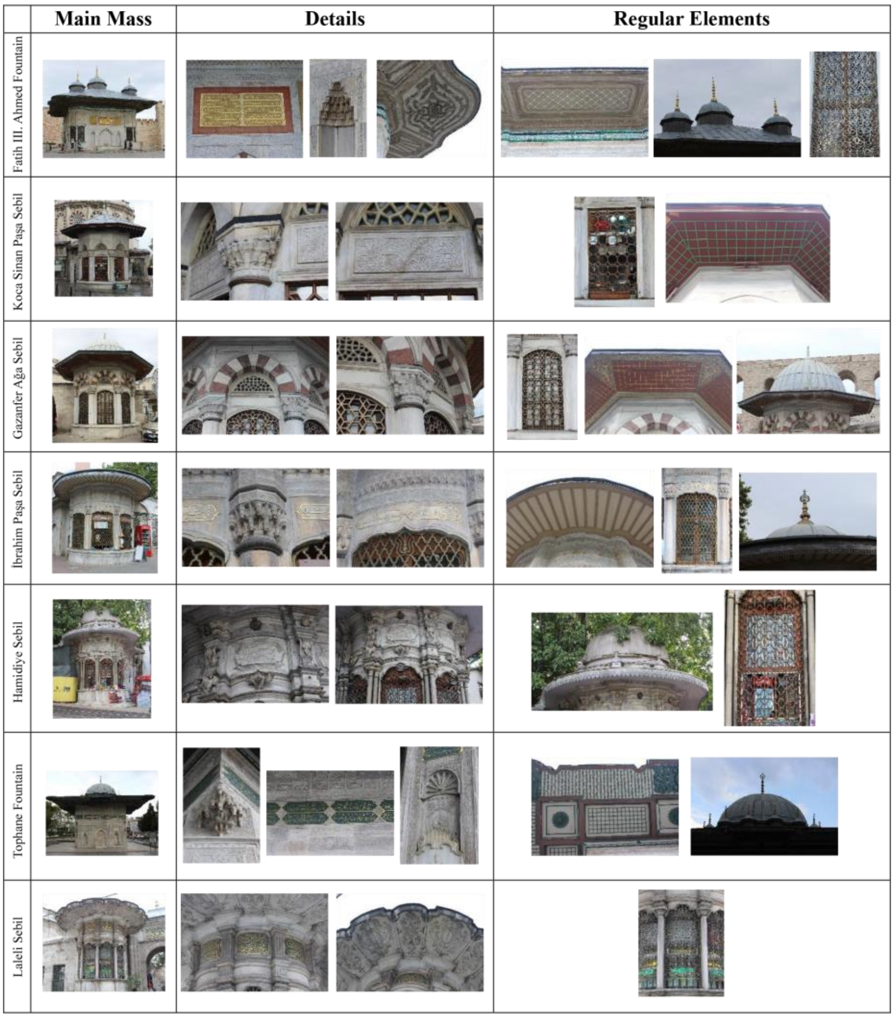


Figure 18. Grouping of elements of fountain examples.

The study can be developed through modeling of fountains from different eras and regions. In this context, as example of fountains from these different eras and regions, German fountain in Istanbul, designed by architect Max Spitta as gift from Germany to Ottoman Empire, and parts of which were manufactured in Germany and assembled in Istanbul, were examined. Typological elements of German fountain were tried to be categorized according to detail, main mass and regular elements groups in study (Figure 19). This preliminary study has tried to create prediction about use of proposed method in modeling fountains from different eras and regions.

	Main Mass	Details	Regular Elements
German Fountain		  	 

Figure 19. Grouping of elements of German fountain.

7. Conclusion

This study presents method for creation of 3D digital models of historical Ottoman fountains through III. Ahmed Fountain. After study mentions heritage value of historical buildings, talks about necessity of 2D and 3D documentation of these structures, which have faced deformation and destruction over time. In this context, models created during 3D documentation of historical buildings have contributions to research, restoration and conservation studies.

Within the scope of study, methods are frequently used in creation of historical building models have been examined and it has been observed that methods have advantages and disadvantages. In this direction, it has been concluded that use of single method in modeling of historical buildings is insufficient. This study proposes modeling method uses multiple technique to reach detailed model in process of creating digital models of Ottoman fountains.

The study, unlike previous ones, examines digital modeling process of historical buildings through Ottoman fountains, categorizes fountains based on typological and physical elements, and presents method proposal aims to determine and apply modeling method suitable for each category and to reach accurate and detailed result model with sub-models created. Method proposal presented in study was studied as case study on III. Ahmed Fountain. This method proposal, which includes geometry-based, photogrammetric and parametric modeling techniques, has been successful in reaching detailed holistic fountain model on III. Ahmed Fountain.

During modeling study, challenges such as physical access restrictions and effect of physical and social factors on data accuracy were encountered in data collection and data visualization stages, but these difficulties were solved by integrated use of different data sets and software. Methods such as photogrammetry used in study were used in creating source together with creation of final model, and multifaceted use of techniques was mentioned and study was enriched. Disadvantages of modeling techniques were tried to be minimized by using supporting software such as ZBrush and Adobe Substance 3D Sampler. Selection of appropriate method for element to be modeled and the fact that study was not limited to single method or tool made significant contribution to study in terms of creating more effective and realistic model.

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1.B.

BUILDING INFORMATICS AND PARAMETRICS - I

RETHINKING TRADITIONAL INDONESIAN ROOF BAMBOO FRAME STRUCTURES BY UTILIZING PARAMETRIC TOOLS AND AUTOMATED FABRICATION TECHNIQUES: A SYSTEMATIC REVIEW

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Abstract. In traditional Indonesian architecture, bamboo and timber-frame structures are essential elements, with roofs being a prominent feature. This is due to the tropical climate conditions that demand such a design. However, the traditional Indonesian hyperbolic-paraboloid roof is at risk of extinction due to modern construction demands, and traditional craftsmanship is gradually being lost. To address this issue, our research investigates which existing parametric design tools and fabrication techniques are suitable for a digital workflow and assembly production of Indonesian traditional roof structures. Through a systematic review and analysis of 19 selected articles, we have categorized the various workflows, tools, and techniques and their suitability to propose and be integrated into a novel Indonesian bamboo-based roof structure fabrication workflow, making it accessible to contemporary architecture.

Keywords: *parametric bamboo, bamboo fabrication, bamboo frame, bamboo roof, bamboo structures.*

ملخص. فى العمارة الإندونيسية التقليدية، تعتبر الهياكل المصنوعة من الخيزران والإطار الخشبي عناصر أساسية، مع كون الأسقف سمة بارزة. ويرجع ذلك إلى الظروف المناخية الاستوائية التي تتطلب مثل هذا التصميم. ورغم ذلك، فإن السقف الإندونيسي التقليدي ذو القطع الزائد والقطع المكافئ معرض لخطر الانقراض بسبب متطلبات البناء الحديثة، ويتم فقدان الحرف اليدوية التقليدية تدريجياً. لمعالجة هذه المشكلة، يستقصى هذا البحث أدوات التصميم البارامترية الحالية وتقنيات التصنيع المناسبة لسير العمل الرقمي وإنتاج التجميع لهياكل الأسقف الإندونيسية التقليدية. ومن خلال مراجعة وتحليل منهجي لـ١٩ مقالة مختارة، قمنا بتصنيف مسارات العمل والأدوات والتقنيات المختلفة ومدى ملاءمتها لاقتراحها ودمجها في سير عمل تصنيع هيكل جديد للسقف الإندونيسي القائم على الخيزران، مما يجعله في متناول العمارة المعاصرة.

الكلمات المفتاحية: *الخيزران البارامترى، تصنيع الخيزران، إطار الخيزران، سقف خيزران، منشآت خيزرانية.*

1. A brief description of a typical traditional Indonesian house

Indonesian architecture is known for the diversity of its traditional housing typologies and construction methods. Inherited from the noble ancestral culture, the traditional houses were constructed using non-rigid timber and bamboo frameworks with a notable emphasis on the distinctive roof geometry (figure 1). The diverse forms of the roofs share a common thread in the expression of roofing steepness, which embodies local wisdom's response to solar radiation and the tropical climate (Prasetyo *et al.*, 2017). They are spread over several islands (figure 1) and follow a particular rule in their local tradition or are driven by culture (Toe and Kubota, 2015). Traditional Indonesian houses have vital elements in ornamentation, symbiosis with external space, transitional, inner space, breathing walls, non-rigid structure, and roof domination (Prasetyo *et al.*, 2017). It has been described terminologically as "*roof-based architecture*" because the name of the traditional house is given based on the shape of the roof (Hardiman, 2005). The roof is linked to the head of a building, showing its dominant proportion compared to the element of the body or building base (stilt houses); using *pilotis* (ground-level supporting columns or stilts) gives the impression of lightness, especially to the heavy roofs.

The roof is a critical element in recognizing and processing building figures, and each tribe represents a different form and shape of houses, especially conspicuously in the roof shape (Nurdiah, 2001). A very sharp upper slope causes the roof to buckle, thereby reducing the absorption of solar energy (Supriatna and Handayani, 2021). Despite the variety of roof shapes in traditional Indonesian houses, the common thread in climate consideration is essential in creating its geometry (Rajendra, 2021) to express the roof's steepness (Prasetyo *et al.*, 2017). Gadang Houses in west Sumatera have a roof that is tapered on both left and right sides, curved inwards on both sides, low in the middle, and elongated in the shape of a buffalo horn (Supriatna and Handayani, 2021). Generally, a traditional house's roof structure is made of bamboo or timber rods and sheets connected through rattan rope and a pin-a-hole join system. It uses bamboo as frame roofing structure material and palm tree fiber or *ijuk* (palm fiber) as covering material affecting thermal conditions inside the house for tropical climate friendly.

However, to limit the scope of this research, three traditional houses representing the west and east of Indonesia are chosen as case studies due to their similarity in the basic roof geometry. The houses are the Gadang House Minangkabau tribe in West Sumatera, the Tongkonan House Toraja Tribe in South Sulawesi, and the Bolon House Batak tribe in North Sumatera. The Bolon (A), Gadang (B), and Tongkonan (C) Houses have similar roof shapes protruding at the end like buffalo horn (Nurdiah, 2001).

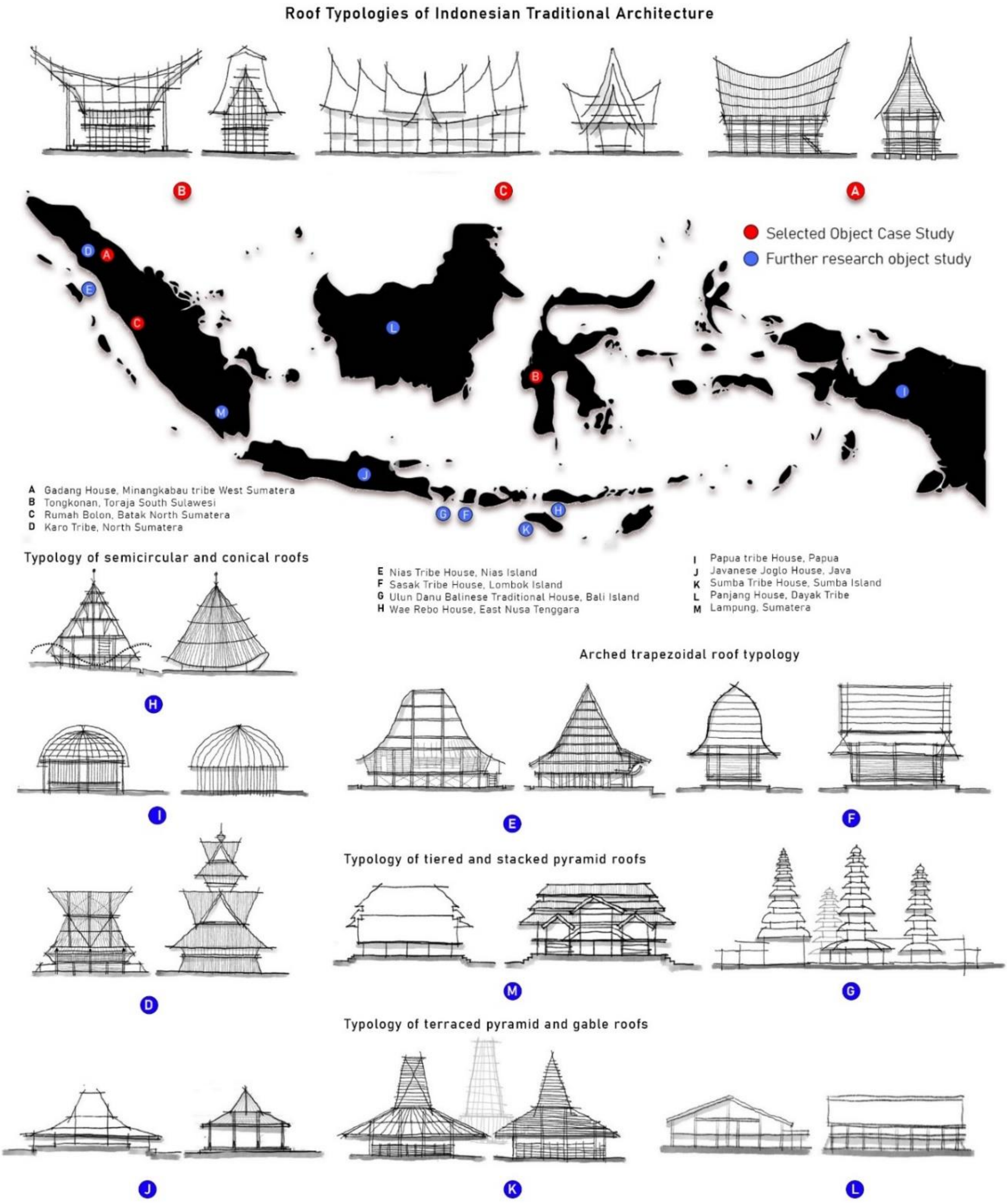
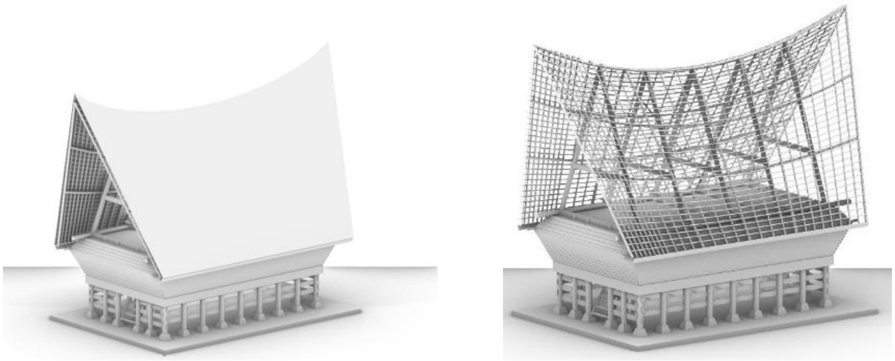
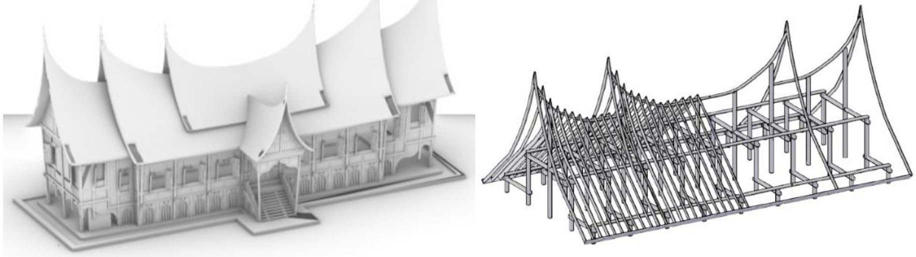


Figure 1. Typological grouping of traditional Indonesian roof shapes spread in the Indonesian Archipelago (Source: authors)

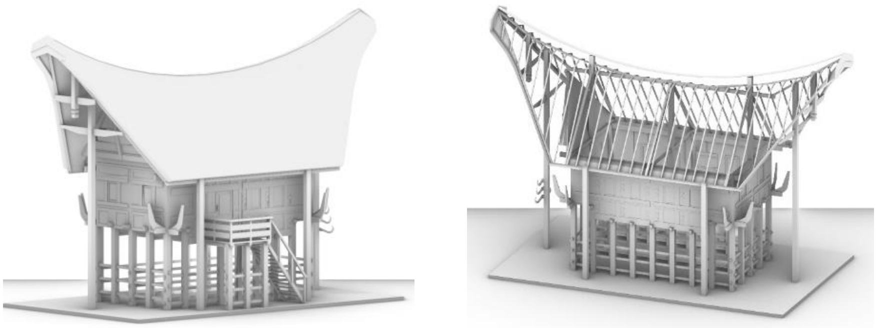
Batak, Gadang, and Tongkonan houses have similar roof shape typologies, and these three tribes are well-known for their protruding shapes, with high-raised roof arches and curving at the top end of the roof. Regardless of their similarity in basic shapes, each has its differences in symmetry and asymmetry of their curve ridge (figure 2). The basic roof geometry has been adopted and translated into many contemporary architectures as new vernacularism, especially in public facilities and local government services office buildings, as the cultural symbolism and architectural representation.



A *Bolon House*, Batak North Sumatera



B *Gadang House*, Minangkabau tribe West Sumatera



C *Tongkonan House*, Toraja South Sulawesi

Figure 2. Selected object case study of traditional Indonesian houses (Sources: authors)

2. Materials and Methods

This systematic review focuses on integrating traditional bamboo frame construction techniques with parametric design and robotic fabrication technologies to make them applicable in contemporary architecture. Consequently, this research answers the following questions:

1. What are the most suitable parametric design, optimization, and fabrication tools that can be utilized in the design process of Indonesian bamboo hyperbolic paraboloid structures?
2. What design and fabrication workflow would be the most suitable to potentially revolutionize Indonesian bamboo-based traditional architecture and make it accessible to contemporary architecture?

We conduct a systematic review to answer our research questions, following a method that consists of three phases, as seen in Figure 3. This includes 1) data collection and filtration by searching specific keywords in the Scopus and CuminCAD databases, selecting journal and conference articles, and 2) analyzing and reviewing selected research of bamboo-related digital architecture and automated fabrication techniques. The selection process filters the most suitable design and fabrication methods by looking into structure type, tools, and techniques. Finally, in stage 3) we categorize the articles according to: a) material and structural system b) the workflow of digital/parametric design and optimization c) digital automated fabrication or assembly methods.

We utilized the databases CuminCAD, which contains papers of conferences; ACADIA, CAADRIA, eCAADe, SIGraDi, ASCAAD, CAAD, and ISARC international academic conferences are summarised and Scopus, which contains journal papers from architecture, engineering, and structural science-related fields, such as Automation in Construction, Construction Robotics, Visualisation in Engineering, and Journal of Building Engineering. The search was conducted using the keywords "bamboo architecture", "parametric bamboo", "bamboo fabrication," bamboo form-finding", and "bamboo structure". The articles were filtered in phase two by removing the review publications and low-relevance articles. The first filtering took place using the database's filtering tools, whereby 256 articles were found. The 256 remaining articles were reviewed by reading their abstracts. The articles not dealing with the robotic fabrication of bamboo structures, materials, and joints were also removed. An additional 238 articles were removed, resulting in the remaining 19 articles we present. In phase three, the remaining 19 articles were systematically categorized and analysed into three categories: 1) Material and structural system, 2) The workflow of digital/parametric design and optimization 3) Digital automated fabrication/assembly methods.

The final 19 selected articles include one book, five journal articles, and 13 conference papers. Eleven articles examined parametric tools in the design stages, four articles only presented the application of parametric modelling and simulation in bamboo material without fabrication, eight articles applied hand bending, manual assembly, and fabrications in the construction process, three articles explored Mixed Reality (AR and VR) during the fabrication process, one article showcased the hybrid augmentation between robot and human collaboration by using mobile robotic arms and AR-based mobile devices, one article demonstrates the use of robotic tools in fabricating flexible and bendable structures, and one article uses mobile robots in constructing bamboo rods structure. These categorized articles are analysed and compared in the final phase to answer our research questions.

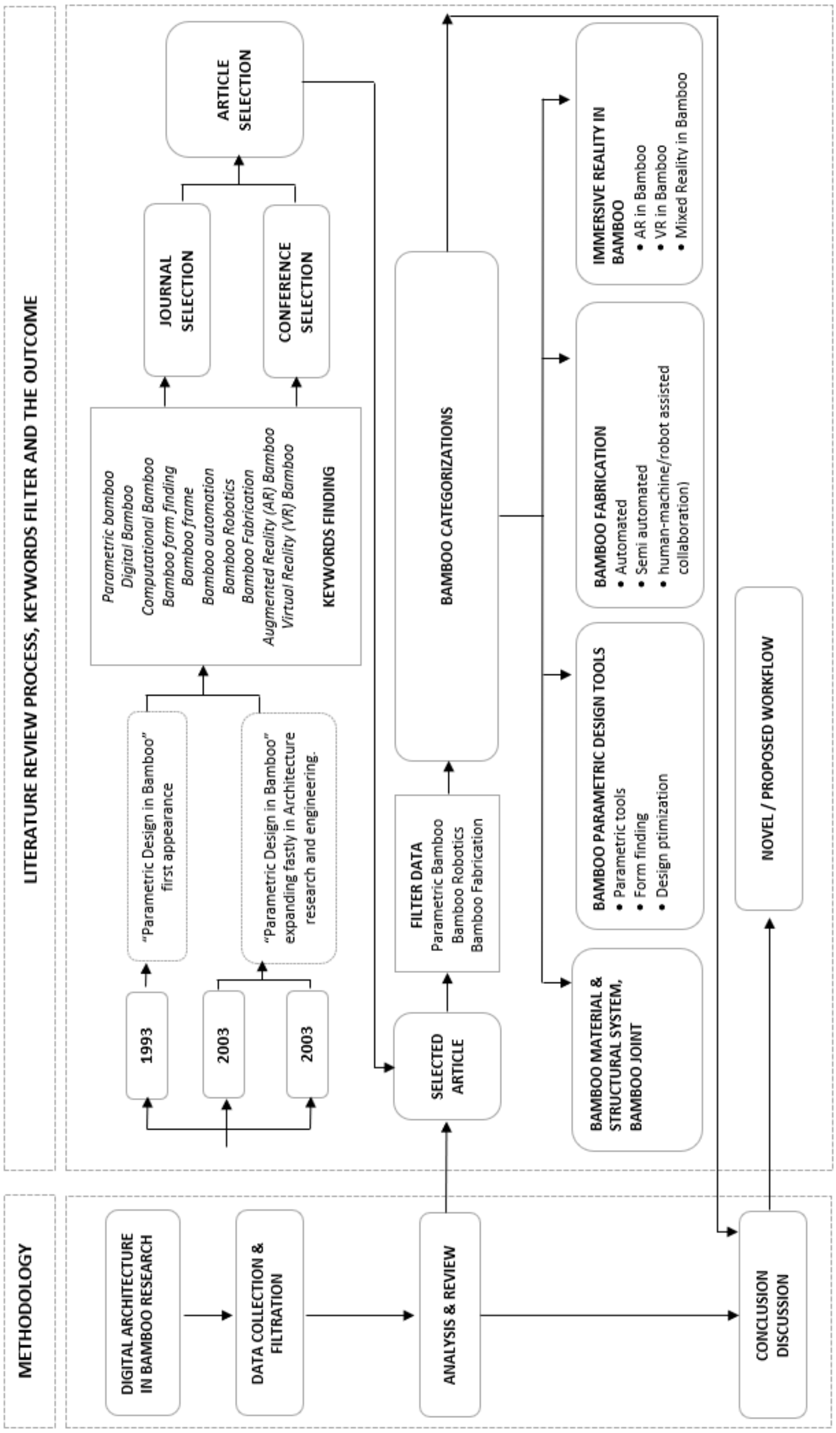


Figure 3. The structure of the systematic review methodology

4. Analysis of the Filtered Papers

4.1 PARAMETRIC DESIGN AND OPTIMIZATION TOOLS

Crolla (2017) showcased the use of parametric design tools for producing complex bamboo geometries in the ZCB Bamboo pavilion, a long-span, bending active bamboo grid shell in CUHK Hong Kong. He used the Kangaroo plug-in for Grasshopper in the form-finding process to simulate physical forces. The digital model geometry is used to extract conventional architecture plans and section and elevation drawings to provide digital data and communicate the bamboo structure application in construction (figure 4).

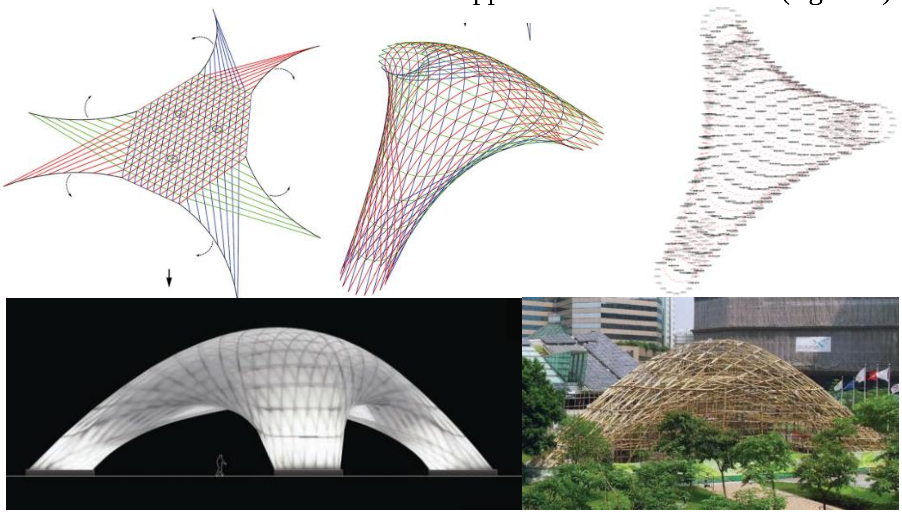


Figure 4. Parametric tools application in ZCB Bamboo Pavilion (Crolla, 2017)

In this research, the parametric model automatically produces the graphic representation of drawings, coordinates, and the dimensions of each element. These data are useful building information used for the construction process, reducing its complexity. Naylor et al. (2022) applied parametric tools in Rhinoceros and Grasshoppers to design a full-culm hyperbolic paraboloid bamboo structure. The form-finding process involves changing the parameters, such as pole length and diameter, adding poles to the grid, and modifying the upper point. Changing the parameters allows the hyperbolic paraboloid bamboo geometry to transform. This allows the overflow of the rainwater to fall towards the two lower points without requiring the additional expense of guttering (figure 5).

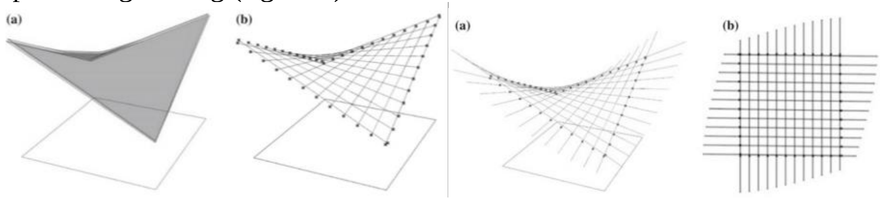


Figure 5. Hyperbolic paraboloid bamboo roof for rain collection strategy using parametric tools (Naylor, J.O., 2022)

Wallisser et al. (2018) designed a tropical bamboo grid shell pavilion as a parabolic hyperboloid grid shell at Rio de Janeiro Federal University utilizing Grasshopper and load simulations with the Karamba Plug-in. They stimulated hands-on empirical testing to predict bamboo structural behaviour and explore the geometry through tension and compression. To generate the bamboo cell division in a freeform structure, a grid shell structure is created instead of polygonal meshes or planar surface, and the surface is divided into a structural tessellation grid shell (figure 6), allowing flexible joints to enable the assembly process.

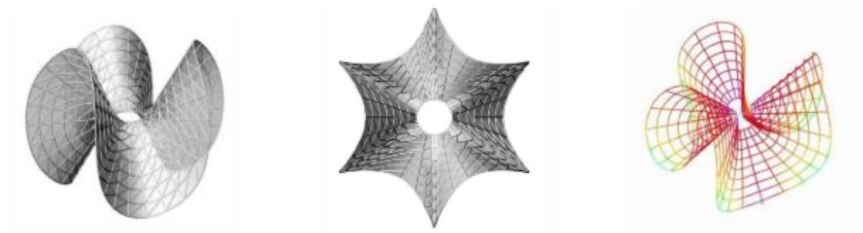


Figure 6. Tropical bamboo grid shell form-finding (Wallisser et al., 2018)

Huang (2022) integrated parametric tools to reinvent the bamboo structure of a traditional Chinese umbrella inspired by cultural values and conventional Chinese craftsmanship. He utilized the Karamba3D and Kangaroo optimization plug-ins for Rhinoceros/Grasshopper. The traditional Chinese bamboo umbrella is transformed into a dynamic and open space geometry (figure 7) but is still rooted in traditional craftsmanship, linking the idea of basic umbrella geometry with novel design tools and new fabrication technology. He argued that to connect traditional material principles with global practice, the new approach of computational tools can enhance the value of local material performances by proposing a new design framework.

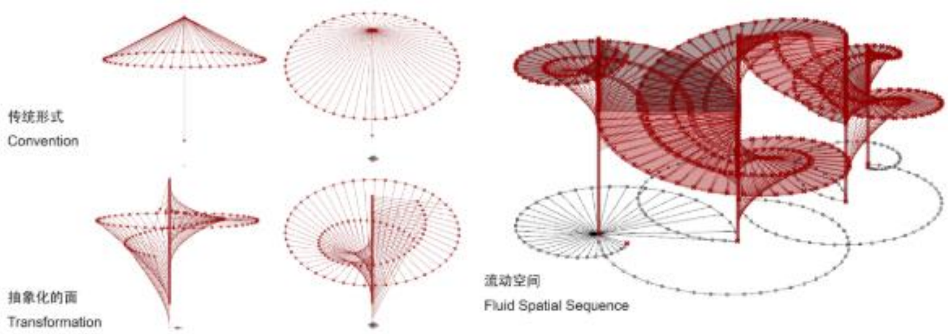


Figure 7. Parametric tools application in designing the bamboo structure of a traditional Chinese umbrella (Huang, 2022)

Wang et al. (2017) investigated the design of a freeform bamboo structure and how parametric tools can systematically be used to deal with the irregularities and joint challenges in bamboo material. A two-stage optimization was applied to support the fabrication of the freeform structure through encoding material properties and freeform shape optimization. This research facilitated direct feedback to the architect on how the cost efficiency of bamboo construction can be achieved by reducing the material used and optimizing the elements of the final structure assembly. The optimization took place using different types of tessellations from the quadrilateral, triangle, and diamond-like patterns. These tools inform how these discrete geometrical elements can be further evaluated and rationalized for fabrication to achieve efficiency and minimum use of material (figure 8). This research displayed that parametric tools can be applied to encode bamboo structures' physical and geometrical attributes. It demonstrated the integration of design optimization, which can simultaneously facilitate the form-finding process systematically and iteratively.

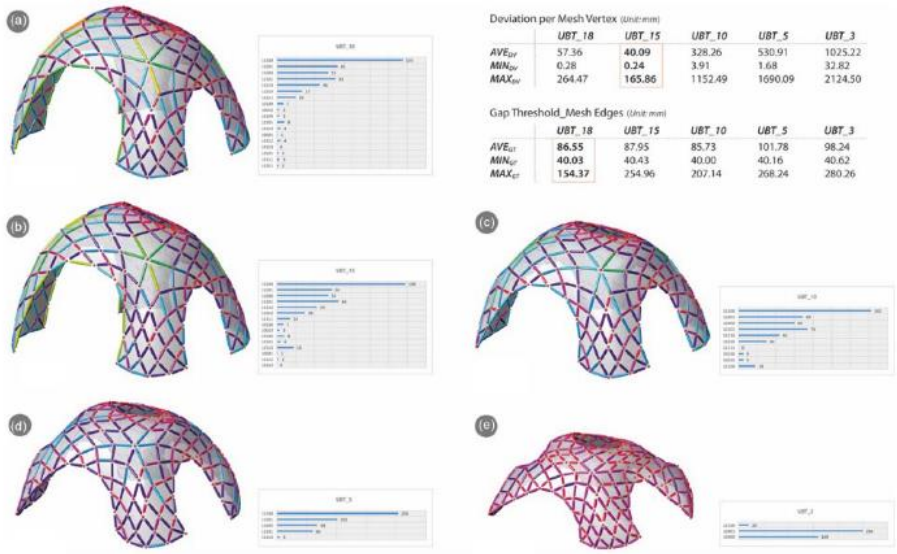


Figure 8. Parametric tools in generating joint systems and surface tessellation in freeform bamboo structures (Wang et al., 2017)

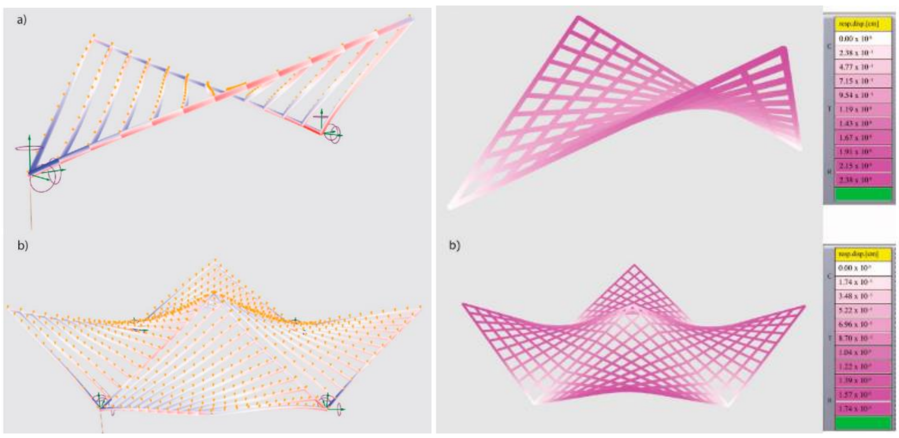


Figure 9. Parametric tools for design exploration of bamboo shell structures (Estrada Meza et al., 2022)

Estrada Meza et al. (2022) used parametric tools in the design exploration of a bamboo shell structure. Specifically, they used the NSR-10 Colombian code for seismic design and construction, analyzed and solved the mechanical behaviour design of double-curved shells, and then compared the result calculation with the values deriving from the Karamba3D, Rhinoceros/ Grasshopper plug-in. Figure 9 illustrates the structural behaviour of two double curvature geometries simulated with parametric software, which has the potential to be applied in the early structural bamboo design process.

4.2 AUTOMATED FABRICATION TOOLS AND TECHNOLOGIES

Robotic construction has allowed faster and more precise production with the advantages of customization, accuracy, and reliability in various work environments and scales (Adel et al., 2018). Along with it, the progression in bamboo integration with digital fabrication has introduced a variety of approaches and methodologies using multiple tools and techniques in several projects, ranging from bamboo pavilion structures using 3D printing joints (Tanadini et al., 2022) to parametric augmented injection in ZCB Bamboo Pavilion (Crolla, 2017) Mixed Reality Collaboration in Bamboo structure (Goepel and Crolla, 2020) 3D Scanning and Augmented reality Bamboo Fabrication (Crolla, 2017), (Wu et al., 2019) and expanding the collaboration process between human-robot cooperation in digital design framework of bamboo culms (Lorenzo et al., 2017).

Nevertheless, bamboo, characterized by its non-standardized nature and distinctive traits of flexibility and versatility, encounters obstacles and challenges when it comes to achieving complete automation in fabrication. The bamboo structures still depend on manual and human labour assembly (figure 10) to address and navigate unpredictable disruptions from a human-free workforce exclusivity in automated robotic construction. Specific bamboo fabrication is still a prominent feature that employs manual techniques and hand bending to construct bamboo structures and installations, both on-site and offsite construction scenarios.

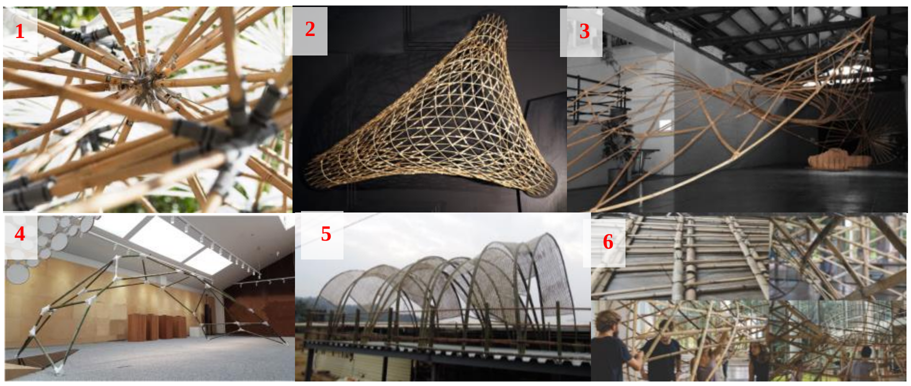


Figure 10. The progression of research in bamboo fabrication: 1) Bamboo pavilion in ETH Zurich (Tanadini *et al.*, 2022), 2) the ZCB Bamboo Pavilion in CUHK Hongkong (Crolla, 2017), 3) Bamboo Lightweight Active bending structure in ITKE Stuttgart (Suzuki, Slabbinck and Knippers, 2020)0, 4) Bamboo[3] project in SUTD Singapore (Amtsberg and Raspall, 2018), 5) the Bamboo Bend Project in NCTU China (Chen and Hou, 2016), and 6) Trefoil Pavilion, a parabolic hyperboloid grid shell (Wallisser, Henriques and Menna, 2019).

Crolla (2017), in the ZCB Bamboo Pavilion in CUHK Hongkong, three layers of bamboo culms were bent and hand-tied into a bending-active triangulated diagrid on-site (figure 11). The pavilion's structure is formulated and validated through digital and physical models, encompassing bamboo prototypes at different scales. In this project, Metal wires were manually used to tie the bamboo culms together, as they offer fire resistance in contrast to conventional knots.

Figure 11. The construction process of ZCB Bamboo Pavilion CUHK (Crolla, 2017)

Achieving full automation in bamboo construction is challenging. Bamboo, as a natural and organic material, exhibits variations in dimension, shapes, and mechanical properties, which make it challenging to automate the fabrication process entirely. On the other hand, bamboo structures also rely on well-designed connections and joints for stability. Hence, in unstructured and non-static environments, especially in construction sites, the robustness and autonomy of such robotic processes are still remarkably low (Edsinger and Kemp, 2007), specifically if applied in fully automated bamboo fabrication. Therefore, during bamboo fabrication, robotic and digital tools still rely on human power assistance in operating, getting involved in fabrication stages, and making critical decisions during the robotic fabrication process (Moniz and Krings, 2016). The assembly and handling of bamboo elements still require skilled human intervention because on-site adjustments and adaptations make it challenging to achieve full automation.

On the other hand, the lack of autonomy limitation in robotic vision will leverage complementary skills and tools that can be integrated with traditional bamboo construction, such as human collaborations and mixed reality, in enhancing the digital construction and fabrication process. The digital environment can provide more intuitive interfaces for robotic fabrication, providing seamless communication and data exchange in collaborative human-robot construction (Aryania et al., 2012), and it can potentially be applied in bamboo fabrication. The constraint limitation in bamboo fabrication will be inclined to expand and openly leverage cooperation in a semi-autonomous manufacturing system between humans, digital tools environment, and robots working together.

A similar scenario was demonstrated in a study by Mitterberger et al. (2022). He explored human-robot collaboration scenarios in assembling wooden structures using rope joints. This experiment employed digital tools and workflows to facilitate augmented human-robot collaboration between two humans and two 6-DoF mobile robotic arms (UR10e) with custom 3D-printed pneumatic grippers. Human operators manually placed the wooden structure and established rope connections with dexterity, while robots assisted in the assembly cycle by accurately placing elements and stabilizing overall structures. This experiment (figure 12) highlights how hybrid human-robot teamwork can enable new pathways toward bamboo automated fabrication.

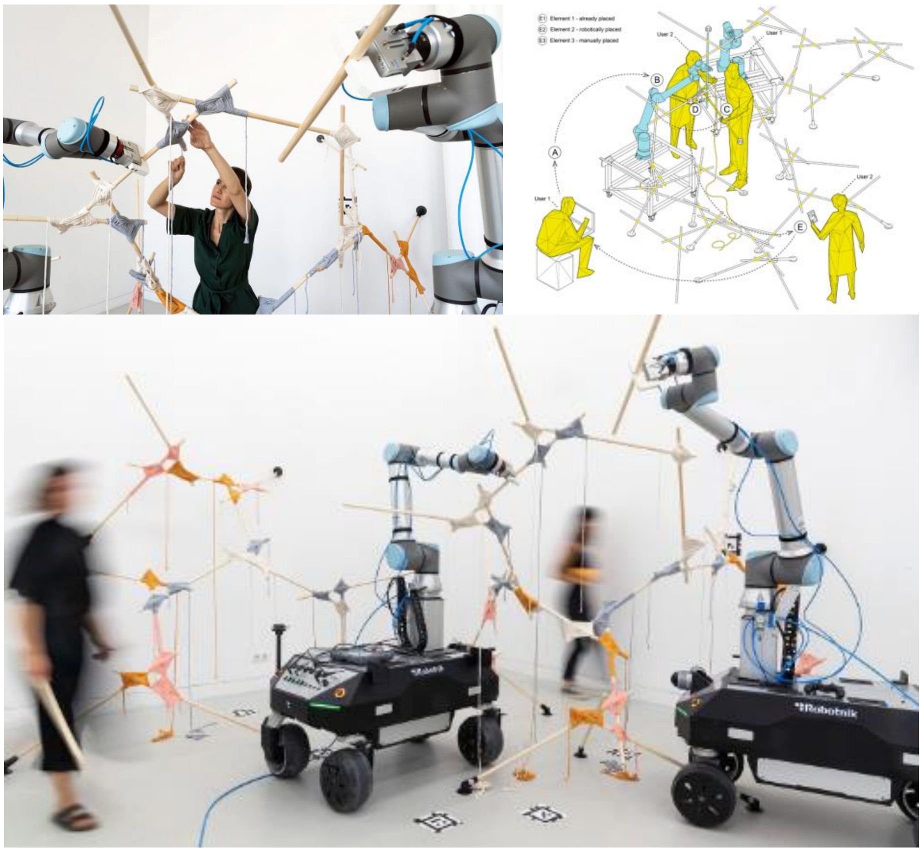


Figure 12. Hybrid human-robot collaboration in assembling wooden structures (Mitterberger et al., 2022)

Brugnaro, Vasey, and Menges (2008) demonstrated a research project titled Robotic Softness, incorporating robotic tools in a bendable and flexible material to assemble woven structures that can be adapted and extended to bamboo structures. The research was inspired by behavioural fabrication logic used by the weaverbird during the self-making of its nest. A 6-axis industrial robot (KUKA KR 125/2) fabricated three-dimensional woven structures with rattan material (figure 13), and it was operated with an online agent-based system, a custom weaving end-effector, and 3D scanning for coordinated sensing strategy.

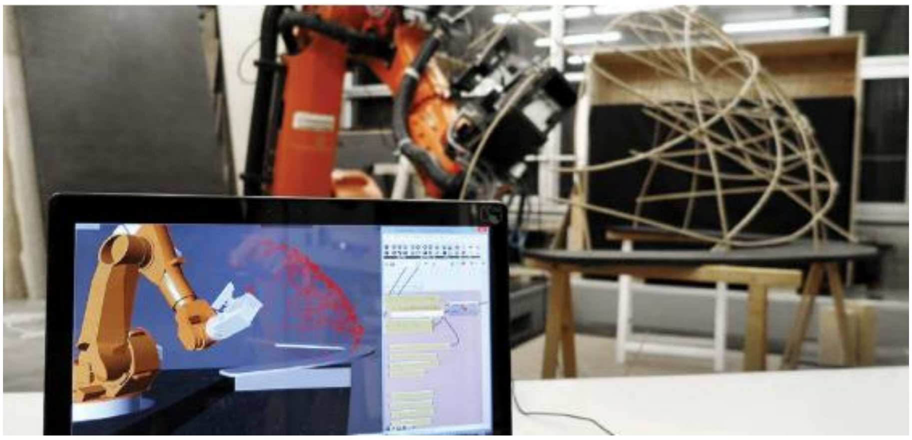


Figure 13. Robot technology applications on bendable material fabrication (Brugnaro, Vasey, and Menges, 2008)

This technique is particularly tailored for the weaving process. It showed that natural materials with organic geometry can be fabricated with robotic technology (figure 14). However, this strategy needs deeper exploration to determine whether this framework adapts to bamboo fabrication scenarios. This research indicated that integrating computational design and innovative fabrication techniques with natural material and organic construction processes can be implemented.

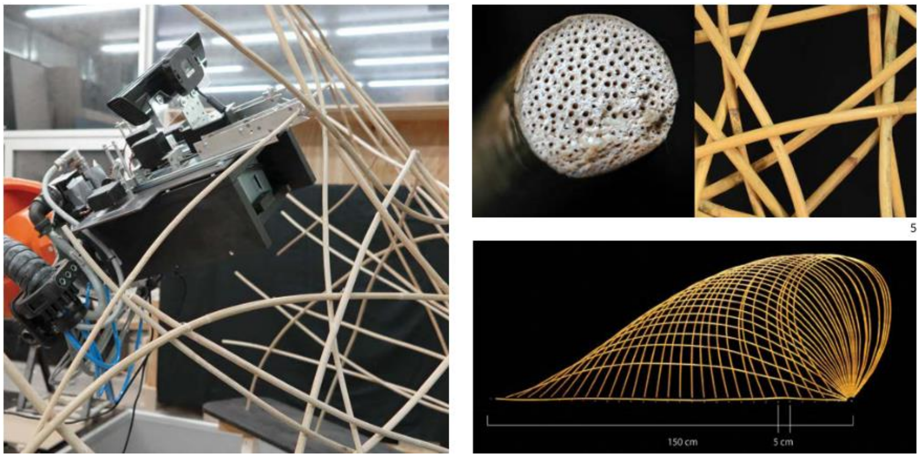


Figure 14. Employing Robot technology for the assembly of bendable materials (Brugnaro, Vasey, and Menges, 2008)

Another robotic system utilized in bamboo rod construction was presented by Lochnicki et al. (2021) in an active-bending light touch assembly for a bamboo bundle structure project. They used mobile robots that behaved toward bamboo dynamic characteristics and assembled the frames by teaching the robots with a particular control policy to bend bamboo bundles (figure 15) using deep reinforcement learning (DRL) algorithms. They constructed bamboo bundles with metal zip-tie joints and steel anchor base foundations. This research showcased the potential to unlock robotic building practices with bamboo as a rapidly renewable material and promote sustainable construction.

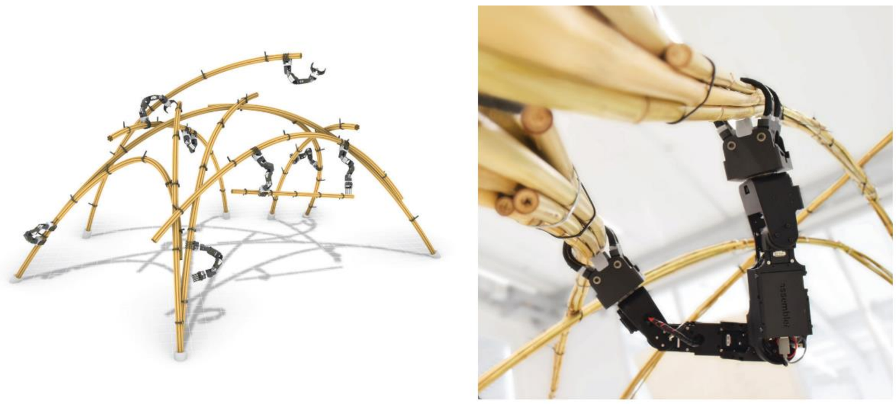


Figure 15. Mobile robot prototypes used in feasibility studies assemble lightweight bamboo bundle structures (Lochnicki et al., 2021)

During the physical assembly, the mobile robot could use its weight and momentum to bend the bamboo rod bundle element into the determined position. The robot could adjust its swinging even when external factors influenced the bending response from the material. The ability of robots to connect bundles was achieved by hard-coding the mobile robots to grasp and connect them to the other existing bundles in the structures (figure 16).

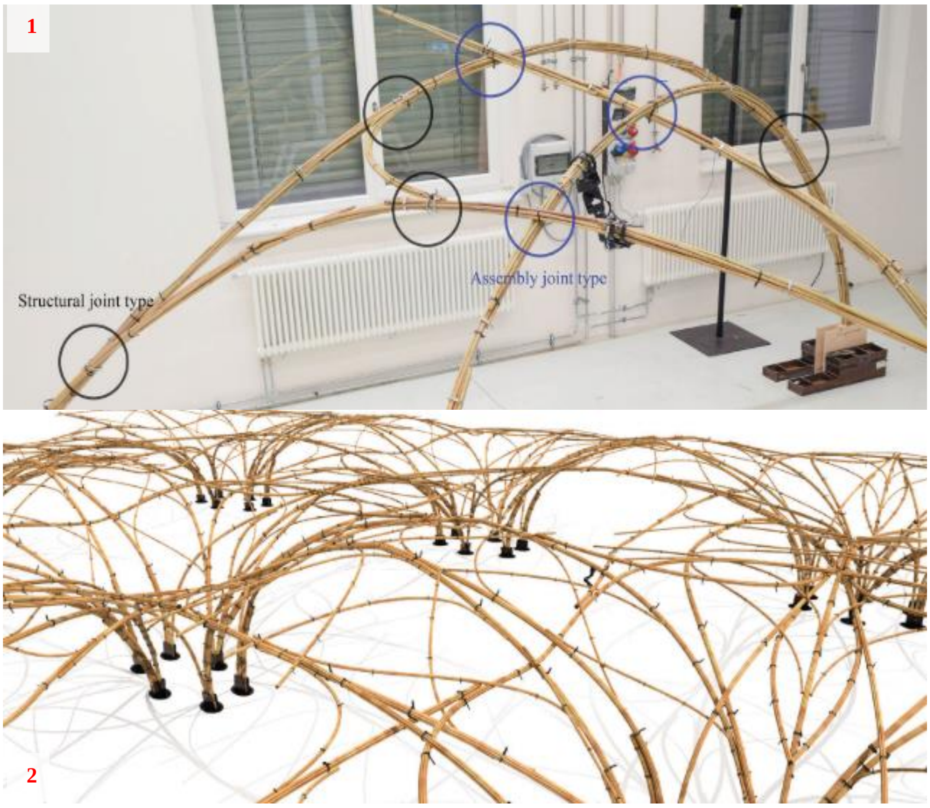


Figure 16. The assembly process of bamboo rod bundle structures with mobile robots: 1) join types of the construction system. 2) The speculative outlook of the whole structure of active bending bamboo structures ((Lochnicki et al., 2021)

In addition, mixed reality tools (AR and VR) technologies can also assist in visualizing and experiencing bamboo structures before, during, and after their physical construction. These technologies provide an immersive environment to explore geometry during the design stages, assess spatial qualities, and make informed decisions during the design and fabrication stages. Several bamboo projects have applied to incorporate AR for fabrication stages (figure 17). Mixed reality tools in Bamboo fabrication can stimulate dialogue and collaborate in creative production and augmented craftsmanship, providing a greater mechanism and diverse design output (Goepel and Crolla, 2020).

Figure 17. Mixed reality applications in the fabrication of bamboo structures: 1) Bamboo Pavilion Diecui Gallery in China (Kenan Sun, Tian Tian Lo, Xiangmin Guo, 2022), 2) Rawbot Bamboo project, a Mobile AR Assembly in UCL: United Kingdom (Wu *et al.*, 2019), 3) Argan Bamboo installation project in CUHK Hongkong (Goepel and Crolla, 2020)

Lorenzo et al. (2017) used a 3D scanner attached to a robotic arm to get bamboo culms' physical and geometric properties as digital data for bamboo pavilion construction (figure 18). They utilised sensor technology to monitor bamboo materials' performance and structural behaviour as a supporting tool for bamboo fabrication. This tool provided real-time data on factors such as stress and movement to ensure structural integrity and longevity of bamboo construction. Various sensors can be employed to monitor and analyze the performance behaviour of bamboo structures, such as strain sensors for measuring deformation strain in bamboo elements, accelerometers for measuring acceleration or vibration, and load cell sensors to measure loads on bamboo components or connections.

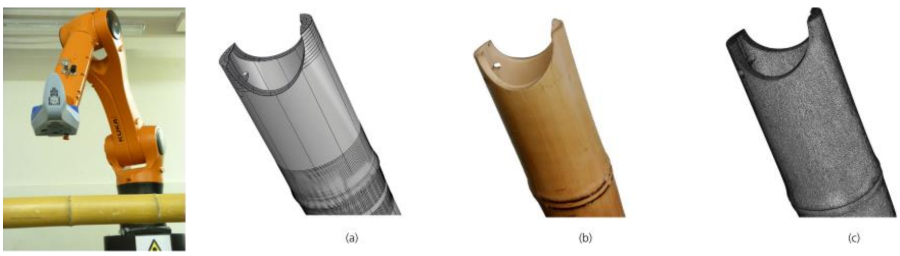


Figure 18. Robotic tools and 3D sensing applications in bamboo fabrication (Lorenzo et al., 2017)

In summary, we present a table (Table 17) categorizing all 19 research projects according to their publication type, materiality, structural system, digital design, optimization tools, and fabrication methods. By analyzing and evaluating them, we propose a novel bamboo fabrication workflow to bridge the gap between traditional architecture and utilizing the latest technology.

TABLE 1. The scope of digital design, optimization, and fabrication methods is examined across the 19 articles.

NO	BAMBOO & DIGITAL FABRICATION RESEARCH	TYPE OF PUBLICATION	MATERIAL	STRUCTURAL SYSTEM	DIGITAL DESIGN & OPTIMISATION TOOLS	FABRICATION METHODS	REFERENCES
1	Exploring the potential of equilibrium-based methods in additive manufacturing: the Digital Bamboo Pavilion	JOURNAL	Bamboo small poles as an ultra-lightweight structure with 3D Printing Join	Spatial truss with post-tensioned cable	Not mentioned	Manual assembly with 3D printing Joint	(Tanadini *et al.*, 2022)
2	Computational Bamboo: Digital and Vernacular Design Principles for the Construction of a Temporary Bending-Active Structure	CONFERENCE	Bamboo laths and jute cords	Lightweight Active bending structure	Rhinoceros & Grasshopper. ElacticSpace for numerical form-finding	On-site assembly, Hand bending	(Suzuki, Slabbinck and Knippers, 2020)
3	Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials	JOURNAL	Bamboo triangulated diagrid shell, lightweight translucent glass-fibre reinforced polymer membrane.	Bending active grid shell structure,	Rhinoceros & Grasshopper Plugin, Kangaroo for phisical force simulation engine	Various scales of 3D scan prototyping before building a full-scale model	(Crolla, 2017)
4	Bamboo 3	CONFERENCE	Bamboo poles and 3D printing joint and connectors	Truss structures	Not mentioned	Visual sensing for material properties and applied in a digital model Manual assembly	(Amtsberg and Raspall, 2018)
5	Design with a bamboo bend, bridging natural material and computational design	CONFERENCE	Bamboo strips	Bending and curvature construction	Parametric tools Rhinoceros & Grasshopper Plug-in	Manual bending and assembly	(Chen and Hou, 2016)
6	Digital construction of bamboo architecture based on multi-technology cooperation	CONFERENCE	Bamboo Pole	Force bearing stricture	Not mentioned	AR, 3d scanning, robot-aided construction, 3d printing and design rules	(Kenan Sun, Tian Tian Lo, Xiangmin Guo, 2022)
7	Rawbot, A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo	CONFERENCE	Bamboo pole with custom joint	Pole Bamboo Structure	Not mentioned	AR Assembly	(Wu *et al.*, 2019)
8	Tie a knot:human–robot cooperative workflow for assembling wooden structures using rope joints.	JOURNAL	Wood stick and rope joint	Wood frame structure	Not mentioned	Hybrid Augmented Human-Robot, two mobile 6-DoF mobile robotic arms (UR10e) with custom 3D-printed pneumatic grippers and two humans	(Mitterberger *et al.*, 2022)

NO	BAMBOO & DIGITAL FABRICATION RESEARCH	TYPE OF PUBLICATION	MATERIAL	STRUCTURAL SYSTEM	DIGITAL DESIGN & OPTIMISATION TOOLS	FABRICATION METHODS	REFERENCES
9	BIM Bamboo: a digital design framework for bamboo culms	CONFERENCES	Bamboo pole	Bamboo pole gridshell	BIM Modelling, Numerical simulations	3D scanning Attached to a robotic arm, performance monitoring robotic prototyping	(Lorenzo *et al.*, 2017)
10	Protection by Generative Design, designing for full-culm bamboo durability using sunlight-hours modelling in Ladybug	CONFERENCE	Full culm bamboo	Only simulation for solar roof protection	Rhinoceros 3D & Grasshopper, Ladybug plug-in	No Fabrication Only simulation	(Naylor, 2021)
11	Augmented Reality-Based Collaboration Argan, A Bamboo Art Installation Case Study	CONFERENCE	Bamboo splits	Free form Art bamboo Installation	Rhinoceros 3D & Grasshopper	Holographic with Microsoft Hololens, AR tools-based assisted manual assembly, Smartphone.	(Goepel and Crolla, 2020)
12	Applying Design Tools for Full-Culm Bamboo	CONFERENCE	Bamboo pole	Hyperbolic paraboloid, bamboo grid shell structure	Rhinoceros 3D & Grasshopper, NURBS geometry, Kangaroo Plug in	Manual assembly Full-scale prototyping	(Naylor, Stamm and Vahanvati, 2022)
13	Encoding bamboo's nature for freeform structure design	JOURNAL	Bamboo	Free form structure	Rhinoceros 3D & Grasshopper, Galapagos Plug-in	Only modelling and simulation	(Wang *et al.*, 2017)
14	The Opportunities and Challenges of Using Parametric Architectural Design Tools to Design with Full-Culm Bamboo: Case Study: A Design for a Hyperbolic Paraboloid for Gutter-Less Rainwater Capture Using Full-Culm Bamboo	BOOK	Full-culm bamboo	hyperbolic paraboloid	Rhinoceros 3D & Grasshopper Galapagos Plug-in	Only modelling and simulation	(Naylor, 2020)
15	Weaving physical-digital networks: Brazil-Germany integration experience	CONFERENCE	Bamboo poles and strips	Bamboo freeform a parabolic hyperboloid grid shell	Rhinoceros 3D & Grasshopper Karamba Plug-in for loads simulations	Manual assembly Full-scale prototyping	(Wallisser, Henriques and Menna, 2019)
16	Integrating Computational Design and Traditional Crafts, A Reinvention Of Bamboo Structures	CONFERENCE	Bamboo	Umbrella free-form structure	Rhinoceros 3D & Grasshopper, Karamba Plug-in for Structural analysis, Kangaroo Plug-in	Manual fabrication	(Huang, 2022)

NO	BAMBOO & DIGITAL FABRICATION RESEARCH	TYPE OF PUBLICATION	MATERIAL	STRUCTURAL SYSTEM	DIGITAL DESIGN & OPTIMISATION TOOLS	FABRICATION METHODS	REFERENCES
17	Design Exploration of Bamboo Shells Structures by Using Parametric Tools	JOURNAL	Bamboo structures	double-curved shells	Rhinoceros 3D & Grasshopper, Karamba 3D Plug-in for Structural analysis, Parametric design, and optimization for the early structural design stage	Only modeling and simulation	(Estrada Meza *et al.*, 2022)
18	Robotic Softness: An Adaptive Robotic Fabrication Process for Woven Structures	CONFERENCE	Rattan woven structure	3-dimensional freeform woven structures	Rhinoceros3D and Grasshopper/RhinoPython	6-axis industrial robot, a KUKA KR 125/2	(Brugnaro, Vasey and Menges, 2008)
19	Co-Designing Material-Robot Construction Behaviors: Teaching distributed robotic systems to leverage active bending for light-touch assembly of bamboo bundle structures	CONFERENCE	Bamboo rods bundle structures (diameters 1.0 to 1.8 cm) Joint: metal zip-tie joints and steel anchor.	Active Bending structure	Not mentioned	Mobile Robots with Deep Reinforcement Learning (DRL)	(Lochnicki *et al.*, 2021)

5. Findings and Conclusions

Our conclusion focuses on answering our initial research questions: What are the most useful and applicable parametric design, optimization, and fabrication tools that can be utilized in the design process of Indonesian bamboo hyperbolic paraboloid structures? Of the 19 chosen articles, 12 employ parametric design tools as digital design strategies, with Rhinoceros and Grasshopper being the most prevalent and practical choices. Supplementary plug-ins such as Kangaroo, Ladybug, Karamba, and Galapagos find utility in structural, environmental, optimization, and simulation tasks. Solely one article integrates BIM Modeling alongside numerical simulations for bamboo digital design.

What design and fabrication workflow would be the most suitable to potentially revolutionize Indonesian bamboo-based traditional architecture and make it accessible to contemporary architecture? Eight of the eighteen selected articles utilize manual fabrication and assembly, including hand bending and on-site manual assembly. Four articles demonstrate the application of mixed reality (VR and AR) cooperation during the fabrication and assembly process, and three articles applied robotic technology consisting of mobile robotic arms (UR10e) with custom 3D-printed pneumatic grippers, 6-axis industrial robot, a KUKA KR 125/2, and the mobile robots with deep reinforcement learning (DRL) algorithms during fabrication of the structures. Additionally, one article shows the potential use of robotic tools attached to 3D scanning sensors during the material selection. Furthermore, our findings show four articles about bamboo digital and parametric design that were only conducted in the modelling and simulation phase without fabrication stages.

These projects relied on manual fabrication and assembly indicating that it is the most popular, pragmatic, reliable, and effective approach. Using mixed reality tools can enrich the various digital fabrication strategies in bamboo structures. Three articles have demonstrated the potential use of robotic technology involvement during the fabrication and assembly stages; however further investigation is required due to the challenges of stability and unpredictable disturbances to achieve full automation in bamboo fabrication. Our deduction indicates that achieving our fabrication research objectives will require integrating a multifaceted approach of tools and techniques to effectively navigate and maximize human-robot collaboration across different stages of the fabrication workflow.

5.1 PROPOSED WORKFLOW

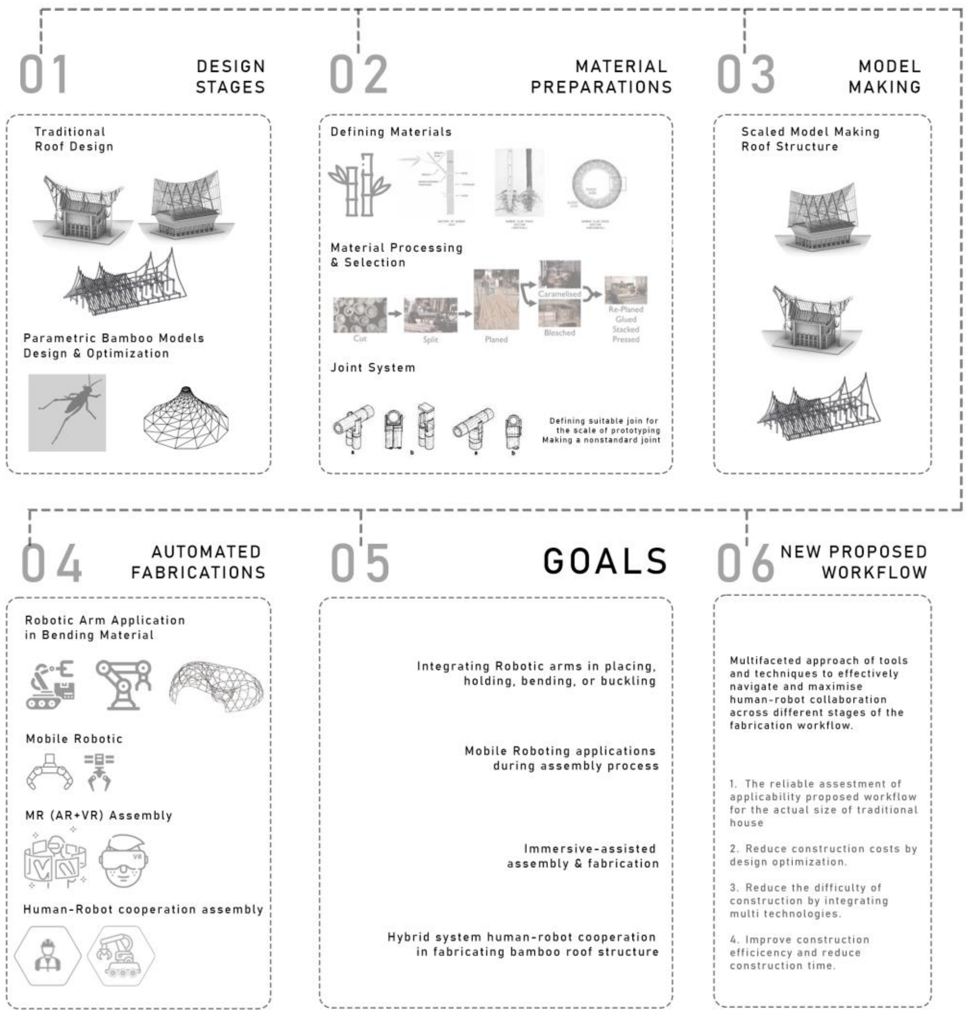


Figure 17. The review leads to a proposed novel workflow to reimagine the digital design and fabrication of traditional Indonesian roofs.

The research question also touches on our research methodology's potential to move beyond traditional Indonesian bamboo architecture. Hence, we propose a new workflow (figure 17) based on the literature review findings. We start with applying parametric design and optimization for traditional roof structures based on collecting and analyzing data about the dimensions and conventional roof geometry frame structures. Once we identify the basic original principle of the traditional roof frame structure, we will design a new scalable roof and apply the proposed workflow for digital design and fabrication of traditional roof frame structures. We optimize the roof structure and fabrication parameters during the design phase to achieve efficient fabrication by evaluating and verifying the entire process scenarios and performances. Regarding the fabrication process, we intend to deploy a hybrid system involving collaborative efforts between humans and robots to construct bamboo roof structures. This is achieved by integrating various technologies at distinct stages of the fabrication workflow.

Our systematic literature review underscores the opportunities and challenges in achieving automation in bamboo construction. As Huang, Z. (2019) has mentioned, the fabrication and assembly of bamboo frame structures historically have been highly dependent on manual operations in construction and difficult to integrate with other standardized building materials. As emphasized by Edsinger and Kemp (2007), in unstructured and non-static environments, especially in construction sites, the robustness and autonomy of such robotic processes are still remarkably low, especially in bamboo material with organic and flexible geometry. However, in this case, the lack of autonomy will encourage complementary skills and tools by providing seamless communication and data exchange in collaborative scenarios between humans and robots (Aryania et al., 2012). Our future work will focus on verifying our proposed framework through design experiments.

Acknowledgements

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SEGMENTED ROOFTOP DATASET GENERATION: A SIMPLIFIED APPROACH FOR HARNESSING SOLAR POWER POTENTIAL USING AERIAL IMAGERY AND POINT CLOUD DATA

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Abstract. With rising global energy demands and climate change concerns, solar energy has gained traction as a sustainable source. However, optimal utilization of solar systems relies on accurately determining rooftop solar potential. This research presents a simplified methodology to generate a comprehensive dataset of segmented rooftops using publicly available aerial imagery and light detection and ranging (LiDAR) point cloud data. The primary objective is to enable precise prediction of solar photovoltaic (PV) capacity on residential rooftops by extracting key geometric features. The proposed approach first preprocesses raw LiDAR data to isolate building points and generates 3D mesh models of rooftops. A mesh analysis technique computes surface normal and tilt angles, stored as RGB images. Masks derived from the 3D meshes are combined with high-resolution aerial photos to extract cropped rooftop image segments. This overcomes the limitations of manually labelling imagery or relying on scarce 3D city models. The resulting dataset provides critical training and validation inputs for developing machine learning models to assess rooftop solar potential. An initial sample dataset of over 1100 residential rooftops in Brisbane, Australia was created to demonstrate the methodology's effectiveness. The workflow is structured, scalable and replicable, facilitating expansion across larger regions to generate big datasets encompassing diverse rooftop configurations. Overall, this research presents an efficient automated solution to harness essential dataset for training Deep Learning models. It holds significant potential to drive solar PV prediction, enabling the optimization of renewable energy systems and progressing sustainability goals.

Keywords: *rooftop segmentation, aerial imagery, LiDAR, point cloud, mesh analysis, solar capacity prediction, parametric.*

ملخص. مع تزايد الطلب العالمي على الطاقة والمخاوف المتعلقة بتغير المناخ، اكتسبت الطاقة الشمسية قوة دافعة كمصدر مستدام. ومع ذلك، فإن الاستخدام الأمثل لأنظمة الطاقة الشمسية يعتمد على التحديد الدقيق لإمكانات الطاقة الشمسية على الأسطح. يقدم هذا البحث منهجية مبسطة لإنشاء مجموعة بيانات شاملة لأسطح المنازل المجزأة باستخدام الصور الجوية المتاحة للجمهور وبيانات السحابة النقطية للكشف عن الضوء والمدى (LiDAR). الهدف الأساسي هو تمكين التنبؤ الدقيق بقدرة الطاقة الشمسية الكهروضوئية على أسطح المنازل السكنية من خلال استخلاص الميزات الهندسية الرئيسية. يقوم النهج المقترح أولاً بمعالجة بيانات LiDAR الأولية لعزل نقاط البناء وإنشاء نماذج شبكية ثلاثية الأبعاد لأسطح المنازل. تقوم تقنية تحليل الشبكة بحساب زوايا السطح الطبيعية وزوايا الميل، ويتم تخزينها كصور RGB. يتم دمج الأقنعة المشتقة من الشبكات ثلاثية الأبعاد مع صور جوية عالية الدقة لاستخراج مقاطع الصور المقطوعة على السطح. ويتغلب هذا على القيود المفروضة على تصنيف الصور يدويًا أو الاعتماد على نماذج المدن ثلاثية الأبعاد النادرة. توفر مجموعة البيانات الناتجة تدريبًا مهمًا ومدخلات التحقق من الصحة لتطوير نماذج التعلم الآلي لتقييم إمكانات الطاقة الشمسية على الأسطح. تم إنشاء مجموعة بيانات أولية لأكثر من 1100 سطح سكني في بريسبان، أستراليا لإثبات فعالية المنهجية. إن سير العمل منظم وقابل للتطوير وقابل للتكرار، مما يسهل التوسع عبر مناطق أكبر لإنشاء مجموعات بيانات كبيرة تشمل تكوينات متنوعة على الأسطح. بشكل عام، يقدم هذا البحث حلاً آليًا فعالاً لتسخير مجموعة البيانات الأساسية لتدريب نماذج التعلم العميق. إنه يحمل إمكانات كبيرة لدفع التنبؤ بالطاقة الشمسية الكهروضوئية، مما يتيح تحسين أنظمة الطاقة المتجددة وتحقيق أهداف الاستدامة.

الكلمات المفتاحية: *تجزئة أسطح المبانى، الصور الجوية، تقنية كشف الضوء والمدى، السحابة النقطية، تحليل الشبكات الرقمية للأسطح، التنبؤ بقدرة الطاقة الشمسية، البارامترية.*

1. Introduction

1.1 LEVERAGING AERIAL IMAGERY AND POINT CLOUD DATA FOR OPTIMIZED PHOTOVOLTAIC ENERGY PRODUCTION.

With rising global energy needs and climate change, solar energy has gained traction as a sustainable source. However, optimal utilization of solar systems relies on accurately determining rooftop solar potential. This is vital in the residential sector, where the effectiveness of rooftop photovoltaic systems relies on accurate assessment. The solar radiation a PV module receives depends on factors like latitude, tilt angle, and time of day (Božiková et al., 2021; Jafarkazemi & Saadabadi, 2013; Xu et al., 2017). Aerial imagery and point cloud data can provide invaluable insights into how much power is likely to be generated for an installation but have been relatively unutilised in previous studies. Presently, PV system identification from remote imagery largely depends on deep learning, which requires extensive training data and manual annotation(Q. Chen et al., 2023; Mellit & Kalogirou, 2021). Given the intensive need for manual annotation in current state-of-the-art methods, there is a compelling demand for a simplified approach to harness solar power potential, employing aerial imagery and point cloud data, reducing reliance on extensive data preparation.

In response to this challenge, this paper introduces a direct method for the generation of a comprehensive dataset of segmented house rooftops. By utilising aerial imagery and point cloud data, the study aims to improve predictions of rooftop solar capacity and thus facilitate the optimisation of solar panel energy production. This simplified approach promises significant implications for solar energy research and the development of more effective solutions for harnessing solar power in residential settings. Consequently, It is a key step towards efficient energy production, aligning with global climate change initiatives.

1.2 GOALS AND IMPLICATIONS OF GENERATING A COMPREHENSIVE DATASET FOR ROOFTOP SOLAR CAPACITY PREDICTION.

Despite progress, gaps remain due to a lack of simplified methods to extract key rooftop features from aerial data. Additionally, prior studies have used diverse techniques for feature extraction, making it difficult to compare the results of different studies and establish a general approach. Another gap is the lack of a large and varied dataset of labelled aerial images that can be used to train machine learning models (Faltermeier, Krapf, Willenborg, & Kolbe, 2023; Ming, Meng, Fan, & Yu, 2021; Mnih, 2013). Many datasets are limited and don't represent all roof types. Furthermore, several factors such as image quality and resolution, building layout, occlusion, and shadows may affect the accuracy of the tilt angle prediction from aerial images (Martín-Jiménez, Del Pozo, Sánchez-Aparicio, & Lagüela, 2020). Existing studies explore solutions through advanced image processing and robust machine learning models (Q. Chen et al., 2023). Finally, Existing methodologies rely mainly on 2D images, limited by the lack of benchmark 3D models. Without accurate 3D models for comparison, the accuracy of the predicted angles obtained from 2D imagery may be compromised (Alidoost, Arefi, & Tombari, 2019).

2. Literature Review

2.1 THE POTENTIAL OF SOLAR POWER IN AUSTRALIA

Solar energy, a renewable resource, exists in two primary technological forms: passive and active. Passive solar technology captures and utilizes solar energy in its inherent form, without conversion into other energy types. On the contrary, active solar technologies, such as solar thermal and photovoltaic (PV) systems, harness and convert solar energy into usable forms like heat and electricity, using electrical and mechanical equipment. These transformed energy forms find applications in various sectors, including heating, drying, cooking, and cooling (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018).
Recently, PV technology has shown potential in both centralized and decentralized systems (Mohanty, Muneer, Gago, & Kotak, 2016). This has led to the proliferation of PV applications in diverse fields such as solar farms, public utilities, and concentrated solar power systems. Notably, residential electricity generation has seen a surge in rooftop PV systems due to their decentralized nature (IRENA, 2019).

2.2 EXISTING DATA RESOURCES AND THEIR LIMITATIONS IN THE FIELD OF SOLAR ENERGY.

In selecting the datasets to be discussed in this following section, our primary criterion was their relevance to our research hypothesis and scope, particularly concerning their capacity to provide information on roof geometry, orientation, and solar potential. One dataset that aligns with these criteria is derived from a novel methodology introduced by Martín-Jiménez et al. (2020). This methodology involves using a combination of LiD Google Earth Satellite (GES) AR and orthoimage data and has been demonstrated to be effective in characterizing the roof geometry for various types of roofs, as illustrated in Figure 1. However, the accuracy of the results can be influenced by the resolution of the input data.

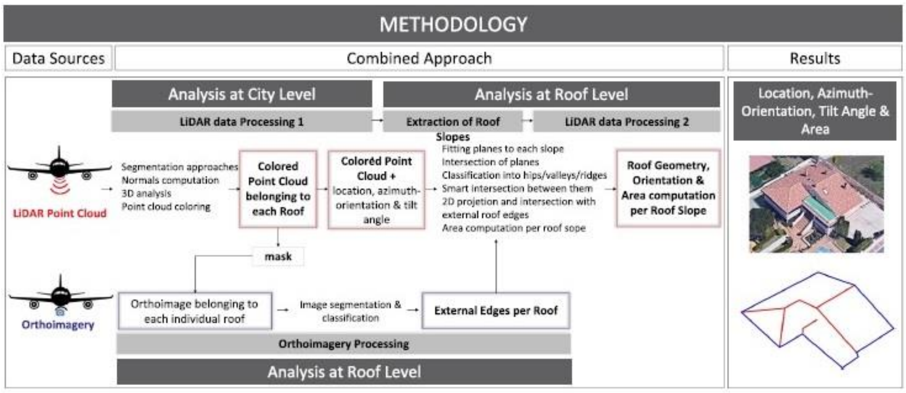

Figure 1 Workflow of the methodology proposed for the 3D characterization of roofs to assess their PV potential (Martín-Jiménez et al., 2020).

Another approach for generating such datasets using aerial imagery and point cloud data was introduced by Krapf, Bogenrieder, Netzler, Balke, and Lienkamp (2022). The authors emphasize the importance of incorporating detailed roof information, including roof segments and superstructures, to enhance the accuracy of potential estimation.

To evaluate the quality of the generated datasets, an annotation experiment was conducted. The experiment involved five annotators labelling superstructures in high-resolution aerial images. The results revealed varying levels of agreement among the annotators for different superstructure classes. While certain classes, such as dormers and PV modules, exhibited high annotation agreement with mean Intersection over Union (IoU) values of 0.70 and 0.68, respectively, other classes, including shadows and unknowns, showed lower agreement with mean IoUs of 0.29 and 0.15, respectively. These findings highlight the challenges associated with labelling small and ambiguous superstructures in aerial imagery.

Additionally, another work that utilized 3D city models and aerial images was conducted by Faltermeier et al. (2023). This paper introduces a unique data-driven approach to improve semantic segmentation of roof segments by automatically creating a large-scale labelled dataset derived from 3D city models. The methodology utilised semantic CityGML data containing detailed roof geometries to generate pixel-wise labels for orthophotos as shown in Figure 2. The study utilizes four datasets:

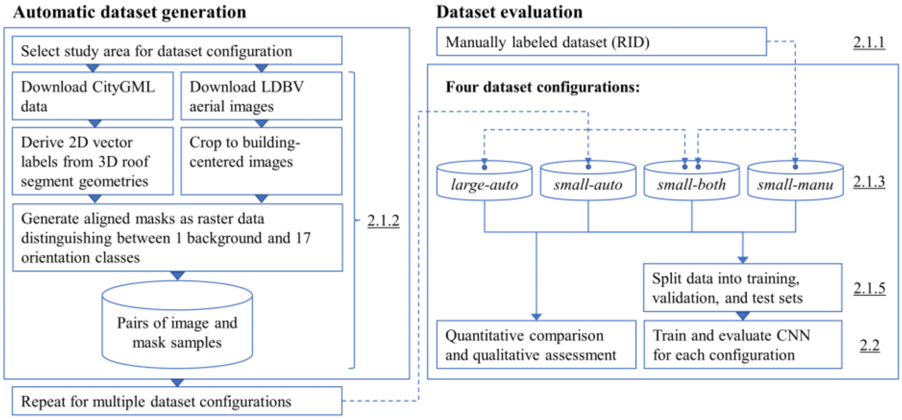

Figure 2 Shows the methodology for generating the dataset by Faltermeier et al. (2023).

1. Roof Information Dataset (RID): A manually annotated baseline dataset with 4312 labelled roof segments across 1878 buildings in a German village, provided as aerial image crops and masks.
2. An auto-labeled dataset of building samples from diverse urban areas was derived from 3D city data and aerial images provided by the Bavarian governmental agency. This dataset aims to compare the effects of various aerial imagery sources and labelling techniques on training results.
3. Large-scale dataset generated automatically from diverse urban and rural areas across Bavaria, Germany with 94,490 samples.
4. Composite dataset combining RID and its automatic recreation.

The methodology uses 3D city models in CityGML format to represent roof geometries. Each roof segment has an associated boundary surface polygon with normal encoding orientation. By projecting polygons onto the 2D plane, aligning with orthophotos, and assigning orientation classes based on azimuth, labels are derived. The datasets served as a basis to train U-Net models for roof segmentation, facilitating a performance comparison between the manually and automatically generated datasets. Applying this technique created a 50-fold larger and more diverse training dataset compared to existing manually annotated data. The large-scale set was leveraged to train a U-Net and showed improved segmentation performance over models trained on small datasets. This demonstrates the potential of automated annotation from semantic 3D city models to advance deep learning for detailed roof extraction, as illustrated in Figure 3.

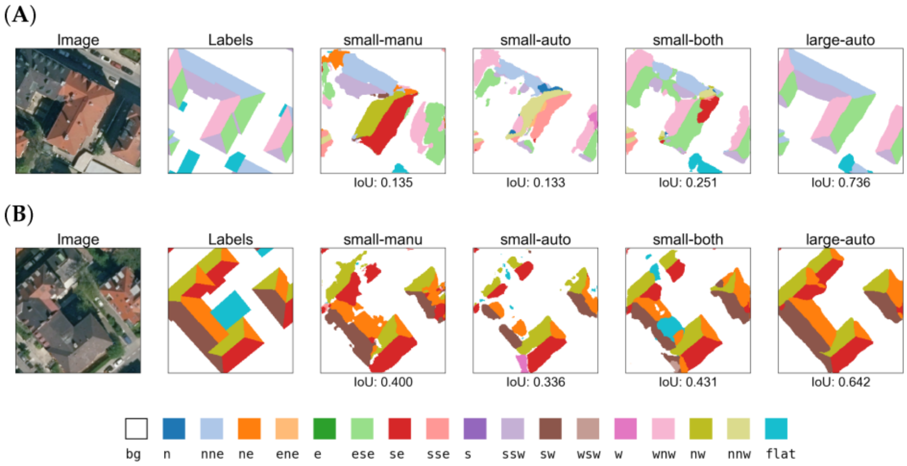

Figure 3 Test samples from the large-scale dataset large-auto at two locations (A,B), and corresponding predictions from all models. IoU with respect to labels is given for each prediction (Faltermeier et al., 2023).

This study's limitation is its reliance on available 3D city data and quality datasets, especially in resource-scarce cities. This constraint highlights an area of research that could potentially focus on developing innovative methods for data acquisition, labelling, and model training in areas with limited access to comprehensive 3D data. Alternatively, some researchers use public datasets for segmented rooftop data. An example of such efforts is the study conducted by Zhang et al. (2022), which forms part of a broader initiative aimed at maximizing solar power potential through the use of aerial imagery and point cloud data. This study presented a methodology for extracting and segmenting rooftop data, to estimate solar power generation capabilities. It achieved this by thoroughly assessing rooftop areas that are conducive to solar panel installation.

The research uses GES imagery, FROM-GLC30 data, and studies 90 Chinese cities. The cities are divided into tiers based on the city administration hierarchy in China, and these cities cover a wide range of economic, political, and geographic conditions. Due to its high resolution and broad coverage, GES imagery is essential for detailed rooftop analysis across various regions. The selected GES imagery undergoes preprocessing to standardize the image quality and a spatial stratified sampling strategy is employed to create balanced samples. Sample processing includes manual labelling of positive and negative samples, which are then divided into training and test sets. The study applies a model known as DeepLabV3+ for rooftop extraction (L.-C. Chen, Zhu, Papandreou, Schroff, & Adam, 2018). DeepLabV3+ is a semantic image segmentation model that can handle features of different scales, which makes it efficient in recognizing varied rooftops from GES images. An ensemble method, using expansion prediction techniques, is then used to handle the issue of splicing gaps in the prediction results from smaller images. The trained model is then used to predict rooftop areas.

Finally, the data records generated by the model are stored and updated regularly to correspond to the urbanization process of different cities in China and are available in the National Tibetan Plateau Data Center. The final rooftop area dataset can serve as a critical resource for further studies, such as estimating the solar power potential of these rooftops. While the study aligns with this research motivations, its manual labelling approach is labour-intensive and can introduce subjectivity and errors into the dataset.

In conclusion, many studies highlight the importance of strong datasets for rooftop solar potential, using diverse methods ranging from LiDAR and orthoimage data to 3D city models and public imagery, each with its advantages and challenges. Despite these advances, a crucial gap remains in the need for simplified, easily replicable, and scalable methods to generate comprehensive, segmented rooftop datasets. This study addresses this gap by presenting a method that does not rely on labour-intensive manual labelling or the availability of detailed city models, to overcome some of the limitations identified in previous works. This research contributes significantly to the field by facilitating the expansion of such studies to areas with limited access to high-quality 3D data or resources for manual labelling. By doing so, the accuracy and efficiency of rooftop solar potential assessment could be enhanced, promoting optimal installation and efficient utilization of solar panels, and further advancing the global transition to sustainable energy sources. The next section introduces the research methodology addressing existing gaps.

3. Methodology

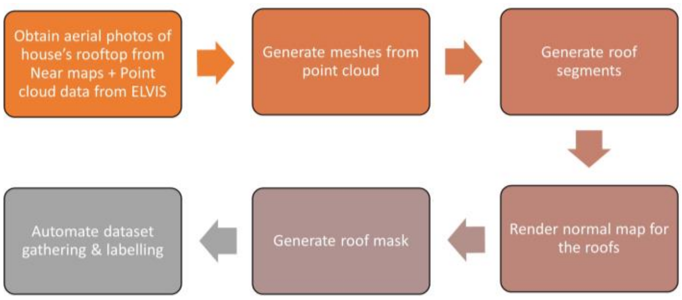

Figure 4 Methodology workflow for producing the dataset.

This study aims to establish a simplified, structured process for creating an extensive dataset of segmented rooftops, leveraging aerial images and point cloud data. The primary objective of this methodology, shown in Figure 4, is to optimize the efficiency of future rooftop solar installations, thereby maximizing their energy output and overall utility. The main hypnosis is that a detailed investigation and assessment of key rooftop attributes including size, architecture, orientation, and colour will empower this dataset to function as a critical resource for training machine learning models to predict solar capacities of commercial rooftops. Methods have been explored as follows:

1. Determined a method for identifying building rooftops using point cloud data and generating simplified meshes.
2. Developed a method for capturing the roof's main surface normal of a rooftop while addressing the challenge associated with recognizing roofing materials, such as tiles, to accurately identify and model the entire rooftop surface.
3. Created a procedure for calculating normal vectors and masks for the rooftops of houses using the previously generated roof segments.
4. Automated the generation of rooftops masks and normal maps.

3.1 DATA RESOURCES

The dataset utilized in this study comprised two data resources. The first is the Queensland LiDAR Data - Brisbane 2019. This data captured high resolution elevation data using LiDAR technology covering the greater Brisbane area, and the details of data are shown in *TABLE 1*.
The second dataset, which is publicly available and subscription-based, is aerial or satellite images from Google Maps and NearMap images *TABLE 2*.

TABLE 1 The Queensland Lidar metadata (Elevation Foundation Spatial Data, 2019)

Parameter	*Value*	*Unit*
Altitude	1250	-
Swath Overlap	60	%
Swath Width	1443	-
Scan Field of View (FOV)	± 30	º
Scan Frequency	1000	kHz
Minimum Density of Ground Strikes/Single Swath	5.5	(calculated)
Average Density of Ground Strikes/Single Swath Clear Open Ground	6.65	(calculated)
Horizontal Accuracy (2 Sigma)	±80	cm
Height Accuracy (2 Sigma)	±30	cm
Cross Track Spacing	0.3	(Calculated)
Down Track Spacing	0.3	(Calculated)

TABLE 2 Data resources.

Data Type	*Database*	*Resource*
Aerial Images	Near Maps aerial images	http://maps.au.nearmap.com/
Aerial images	Google Maps	https://www.google.com/maps/@-27.4846307,153.0428008,1980m/data=!3m1!1e3?entry=ttu
LiDAR Data	ELVIS - Elevation and Depth - Foundation Spatial Data Queensland LiDAR Data – SE Queensland 2018 Project.	https://elevation.fsdf.org.au

3.2 DATA PREPROCESSING

This section outlines the key information of various rooftop characteristics and features that are crucial for developing a reliable prediction model. Improving the model's accuracy relies on a data pre-processing procedure to ensure data consistency by cleaning and structuring the data. This process also enables the extraction of relevant features, such as rooftop size, shape, orientation, and colour. For the specific data type of aerial imagery and point cloud data, pre-processing techniques, like image segmentation, and isolating individual rooftops are important for data labelling. These steps provide the necessary input for training the prediction models, allowing them to learn patterns and correlations between factors that influence rooftop tilt angles. Thus, a well-prepared dataset allows for effective model evaluation, helping to determine the accuracy and reliability of the prediction model and optimizing model parameters for accurate prediction.

The procedure commenced with the preparation of the dataset, which is intended to be used for both training and testing the model. The LiDAR data contains millions of points and represents 28 different classes, including buildings, vegetation, ground, etc. as shown in Figure 5. Handling this data using GIS and QGIS resulted in performance issues due to the complexity and density of the point cloud. Not only did these software packages struggle to manage the large file sizes, but they also had difficulty dealing with the multitude of point classifications. As a result, we turned to the Cloud Compare software, an open-source software package that provides powerful filtering and segmentation tools, allowing for a high level of customization and supporting a variety of file formats. Thus, Cloud Compare allows for more efficient processing and visualization of dense point cloud data by generating smaller, more manageable files. Furthermore, it enabled us to filter the point cloud data to exclusively select points labelled as buildings, effectively reducing the complexity of the data while preserving the information most relevant to this study. This data filtering process is illustrated in Figure 6.

Figure 5 The point cloud classification for the Elvis laz file in Cloud Compare.

3.3 DATA CLEANING AND STRUCTURING

Subsequently, a mesh was generated from the chosen point cloud data and exported as a PLY mesh file, as shown in Figure 7. However, the polygons within this mesh exhibited substantial triangulation and complexity, necessitating further simplification using Grasshopper plugin for Rhino software package, as illustrated in Figure 8.

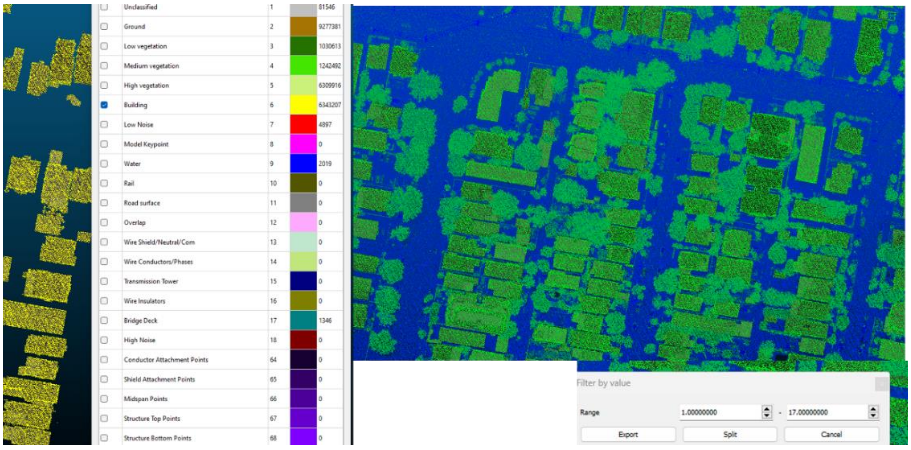

Figure 6 The point cloud data visualised in Cloud Compare (building labelled points).

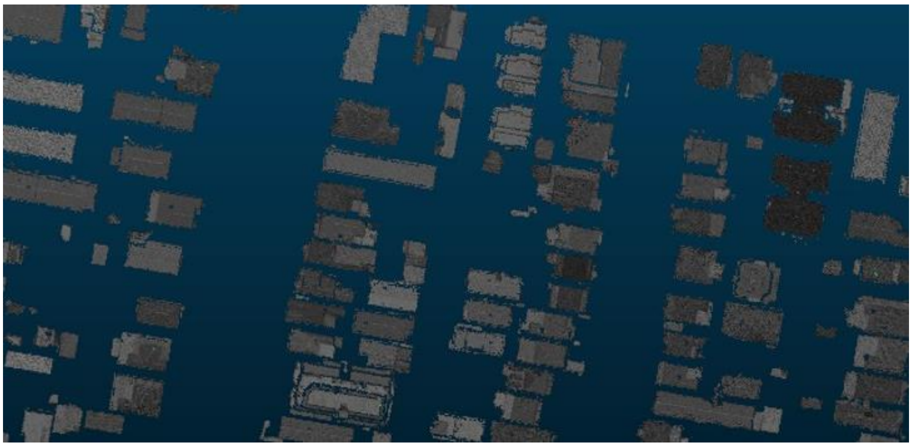

Figure 7 The mesh generated from the point cloud data in Cloud Compare.

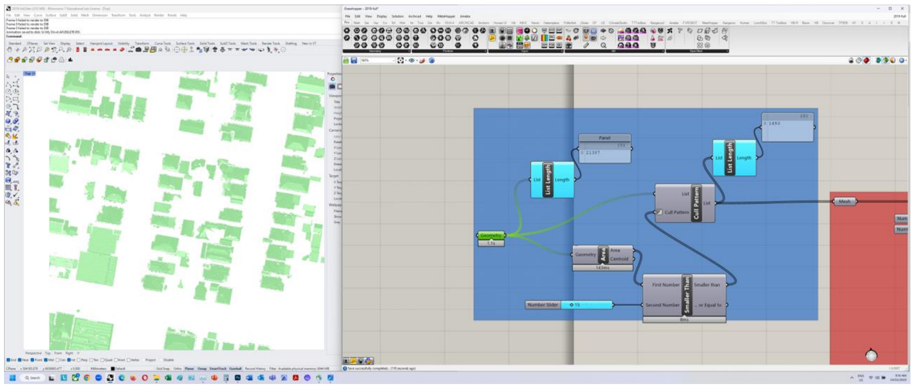

Figure 8 Shows the imported mesh file and the small mesh surfaces that need to be cleaned.

3.4 MESH ANALYSIS TECHNIQUE

Data cleaning was carried out in the Grasshopper plugin for Rhino software package and involved three steps. The first was for cleaning small meshes. To proceed with this step, it is necessary to determine the areas that should be excluded. Since the research is concerned with maximizing solar panel energy production; the PV system energy production value, according to Odeh and Nguyen (2021), is 1796 kWh/kW. The PV system specification consists of 5 modules in parallel and 2 strings, with each module rated at 175W, requiring a minimum area of 12.8 m2, as illustrated in TABLE 3. Consequently, regions with an area of less than 12.8 m2 were removed, as depicted in Figure 9.

Afterwards, the second step seeks to address problems caused by tiled roofs. Roof tiles resulted in very small rectangular meshes capturing each tile, and thus make extracting the roof's main surface challenging, as shown in Figure 10. This was resolved by reconstructing the mesh to reduce the small subsurface from over 20,000 to 50 faces per mesh shown in Figure 11. The value of 50 faces per mesh was determined based on multiple experiments that tested various values, such as 10, 15, and up to 100. These experiments aimed to attain a balance between mesh simplification and accuracy. We note that using the original mesh will result in a significant number of redundant values for the same roof, making this optimization necessary.

TABLE 3 The PV system specification correlated with the roof's top area (Odeh & Nguyen, 2021).

PV module Si-Mono Model FS—175 W	
Number of PV modules in series	5 modules in parallel 2 strings
Total number of PV modules	10 × 175 W each
Total nominal power (@ STC)	1750 W
Array operating characteristics	164 V and 9.6 A
Total module area	12.8 m^2
Inverter Model Sunny Boy SB 1700	
Manufacturer	SMA
Operating Voltage	139–320 V
Power	1.55 kW AC

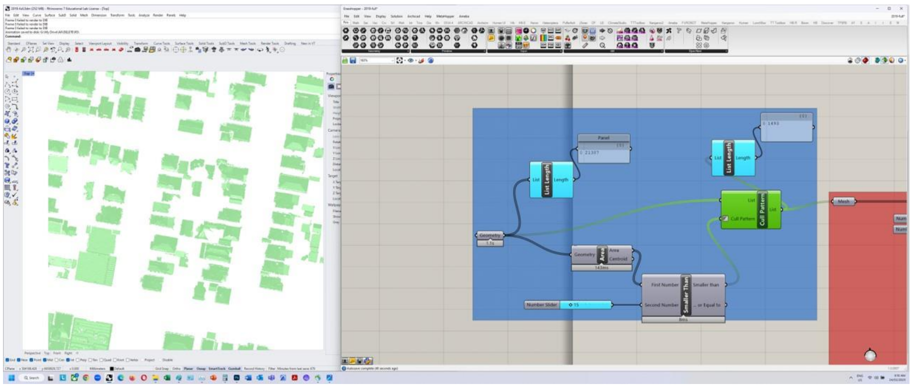

Figure 9 The rooftop after cleaning the small meshes.

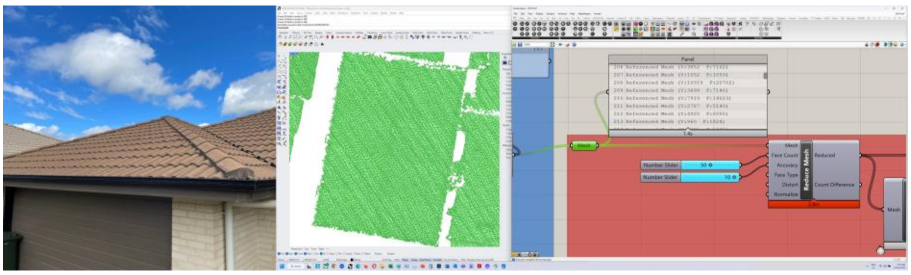

Figure 10 The small meshes emerged from the rooftop tiles.

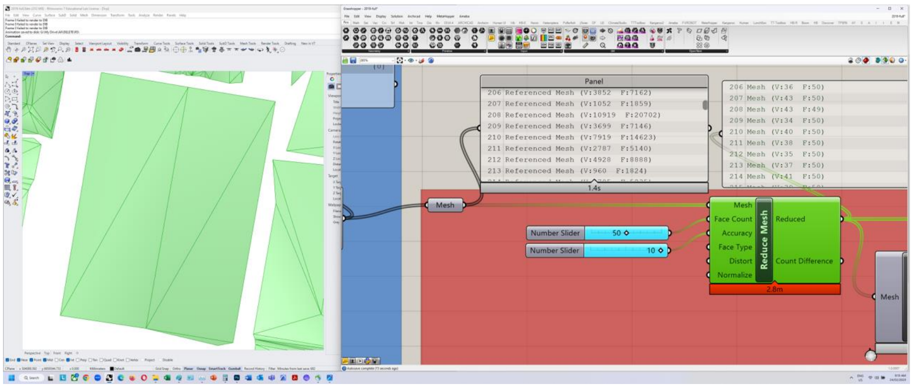

Figure 11 Smoothing the mesh to capture the surface normal.

In order to capture the main surface normal, a mesh analysis technique for the triangle meshes surfaces was performed, to extract the normal vector for each face of the roofs (Gao et al., 2021). The advantage of this technique is in adjusting each vertex while preserving the surface normal (Tu, Weng, Liang, & Luo, 2022). The normal vector was deconstructed into XYZ vector values and remapped into RGB colours, ranging from (-1 to 1) to (0-255), respectively to create a visual representation of the normal vectors as illustrated in Figure 12 and Figure 13. These procedures were then automated and applied to the 1km x 1km area.

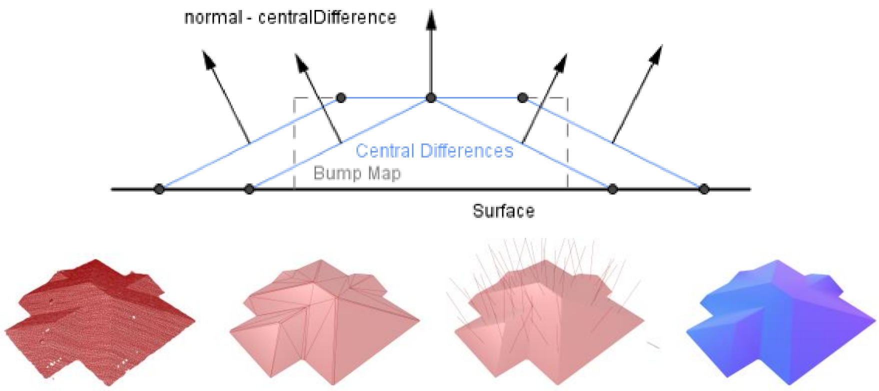

Figure 12 Example of the surface normal where vectors was deconstructed into XYZ vector values (Raimond Tunnel), and the overall process for creating the calculating the normals.

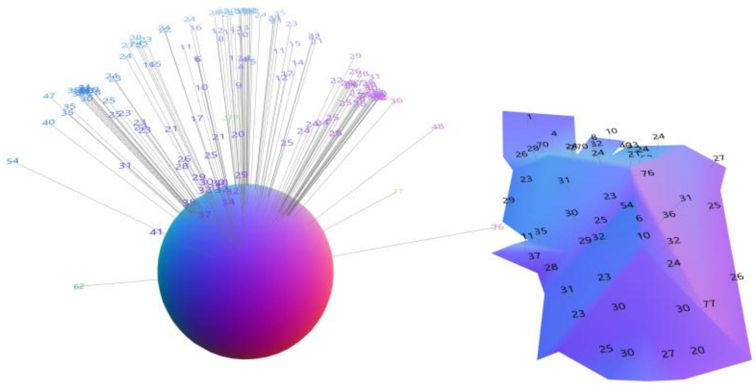

Figure 13 Normal map rendered roofs with the corresponding tilt angle of rooftop meshes with a spherical legend off the normal directions.

4. Dataset generation and Visualization

4.1 GENERATION OF MASK IMAGES FROM THE 3D MESH

After obtaining the 3D mesh for the rooftops, the next step involved generating a mask image from the 3D mesh to isolate the coloured rooftop images from aerial photos. The masked image was then exported to Photoshop, where it was combined with NearMaps for the specified area to create a mask for the rooftops as shown in Figure 14. This approach facilitated faster extraction of the corresponding-coloured images aligned with the 3D rooftop mesh. Finally, rooftop images were initially cropped to a 500x500 pixel size using a Python script, which could be adjusted based on the input image size required by the deep learning model.

4.3 STANDARDIZING IMAGE SIZE

The previously generated dataset sample for a 1×1 km² area in East Brisbane had 1000 × 1000 pixels and comprised 1,100 rooftops Following the optimization of the dataset generation process, an expanded dataset consisting of 150 km² of aerial images of residential areas will be created to provide more than 165,000 labelled images (150*1,100) to generate an adequate data set for training the deep leaning models similar to the data set prepared by *Massachusetts Buildings Dataset* 2020) and Mnih and Hinton (2012).

Figure 14 A sample of house rooftops dataset for an area of 1000×1000 m2.

5. Results and Discussion

In this study, we have leveraged both point cloud data and aerial imagery to generate a simplified, yet comprehensive, dataset of residential rooftop structures which are essential for training a DL model. An easy-to-follow workflow was introduced, making it accessible to individuals not deeply experienced in machine learning techniques, and thus broadening the usability of this approach to generate a large quantity of data covering a large geographic area. Additionally, this simply constructed dataset serves as a valuable resource for training machine learning models to predict and analyse rooftop structures in the context of solar power potential.

Our data generation process hinged on the utility of point cloud data and the use of the Grasshopper plugin for Rhino software for data processing and analysis. The accuracy of the resulting dataset was verified manually, revealing that a few rooftop surfaces had not been adequately detected. This was mainly due to the interference of vegetation point cloud data with the building data during the separation process, which led to some confusion concerning the edges of the rooftops. Despite this minor setback, our study has successfully delivered a new approach to generating a rooftop dataset. Through this research, we have identified several areas of potential improvement and expansion for future studies which are currently under investigation.

One essential area for further exploration is the augmentation of the data resources used in the study. Another area is the incorporation of additional data. While aerial imagery and LiDAR data have proven instrumental in this context, incorporating additional data types such as drone imagery could add an extra layer of richness to the dataset, providing a more robust training set for machine learning models.

Moreover, future studies could concentrate on refining the efficiency of the presented methodology. Although the proposed approach is systematic and comprehensive, it exhibits potential for performance enhancement when tasked with larger regions or a greater number of rooftops. Seeking strategies to streamline the methodology could result in time and computational resources savings.

Finally, it would be beneficial to conduct a more extensive accuracy assessment of the data generated by this approach. Validating the results and comparing them with those from other existing methods could illustrate the relative strengths of the proposed methodology and pinpoint areas where refinement could yield improved predictions.

6. Conclusion

This study introduced a rethink technique for creating a comprehensive dataset of segmented residential rooftops, utilizing aerial imagery and point cloud data. Our approach provides an invaluable resource for training machine learning models to predict rooftop solar capacity.

By employing datasets such as the Queensland LiDAR Data and aerial or satellite images from Google Maps and NearMap, this research was able to generate valuable input for machine learning models through careful data preprocessing, cleaning, structuring, and feature extraction processes. The development of a simple mesh analysis technique and automated method for rooftop masks and normal map generation further emphasized the robustness and precision of this methodology.

The presented work contributes significantly to the fields of solar energy and renewable energy research by providing an efficient way to analyse solar power potential in residential settings. The implications of this research are far-reaching, from assisting in the advancement of renewable energy systems to aiding in achieving sustainability goals and addressing global warming issues. The dataset generation method presented in this study will undoubtedly serve as a catalyst for further research, fostering more accurate predictions of solar potential and assisting in optimizing solar power system installations.

One of the limitations of our study pertains to the accuracy of the point cloud data. This inaccuracy can be attributed to the presence of adjacent vegetation near rooftops and variations in roof materials. Additionally, there are instances where the assigned classes of certain points become mixed. To mitigate these issues, we recommend incorporating more precise point cloud data.

In future work, we plan to utilize the generated dataset to train and evaluate deep learning models. This would provide a robust means of predicting rooftop geometry, further advancing the research on the use of solar energy in the residential sector. Additionally, expanding the geographical coverage of the dataset to other regions would improve its generalizability and enable the application of this approach globally.

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HUMAN-ROBOT CRAFT TRANSFER

Learning from Nabateans carving out methods, techniques, and tools

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Abstract. Traditional methods of carving trenches have been used by Nabateans in quarries locations for centuries, including carving out a large block out of a mass solid of sandstone and continuing carving out processes. This research explores the strategies for sculpting and the structural feasibility needed to assist methods of design generation in tangent. It traces tools and processes used in cutting large blocks for stone quarries and rock-cut buildings for efficient and sustainable methods to train an industrial robot. The research aims to support a revival of the historical global phenomenon approach of carved-out buildings through advanced technologies for fabrication. Through knowledge derived from traditional stone cutting, robotic subtractive/additive processes and robotic fabrication and assembly, the paper aims to develop case studies. By reviewing the current state of the art in digital sandstone carving, and prototyping, the paper discusses craftsmanship and technological development through the concept of carved-out in solid, applied in the context of advanced fabrication and robotic adaptation. This paper reports on a parallel study of the traditional methods of cutting a block out of a solid from one side and the robot adoption of the ancient tools and methods by testing processes iteratively; first through manual investigation and secondly through robotic simulation and tooling with Styrofoam as homogeneous material replacement. The paper discusses the results of digital fabrication and novel knowledge for the human–robot craft transfer.

Keywords: *Carved out solid; Robotic subtractive cutting; human–robot craft transfer, Nabateans methods; stereotomy.*

HUMAN-ROBOT CRAFT TRANSFER: LEARNING FROM NABATEANS CARVING OUT METHODS, TECHNIQUES AND TOOLS

ملخص. لقد استخدم الأنباط الطرق التقليدية لنحت الخنادق في مواقع المحاجر لعدة قرون، بما في ذلك نحت كتلة كبيرة من كتلة صلبة من الحجر الرملي والاستمرار في عمليات النحت. يستكشف هذا البحث استراتيجيات النحت والجدوى الهيكلية اللازمة لمساعدة أساليب توليد التصميم في الظل. وهو يتتبع الأدوات والعمليات المستخدمة في قطع الكتل الكبيرة للمحاجر الحجرية والمباني الصخرية للحصول على أساليب فعالة ومستدامة لتدريب الروبوت الصناعي. يهدف البحث إلى دعم إحياء نهج الظاهرة العالمية التاريخية للمباني المنحوتة من خلال التقنيات المتقدمة للتصنيع. ومن خلال المعرفة المستمدة من قطع الحجر التقليدي، وعمليات الطرح/الإضافية الآلية، والتصنيع والتجميع الآليين، تهدف هذه الورقة إلى تطوير دراسات الحالة. من خلال مراجعة الوضع الحالي للفن في نحت الحجر الرملي الرقمي والنماذج الأولية، تناقش الورقة الحرفية والتطور التكنولوجي من خلال مفهوم المنحوتة في المواد الصلبة، والتي يتم تطبيقها في سياق التصنيع المتقدم والتكيف الآلي. تتناول هذه الورقة دراسة موازية للطرق التقليدية لقطع كتلة من مادة صلبة من جانب واحد واعتماد الروبوت للأدوات والأساليب القديمة من خلال اختبار العمليات بشكل متكرر؛ أولاً من خلال التحقيق اليدوي وثانيًا من خلال المحاكاة الآلية واستخدام الأدوات باستخدام الستايروفوم كبديل متجانس للمواد. تناقش الورقة نتائج التصنيع الرقمي والمعرفة الجديدة للنقل الحرفي بين الإنسان والروبوت.

الكلمات المفتاحية: منحوتة صلبة، القطع الآلي بالروبوت؛ الانتقال الحرفي بين الإنسان والروبوت، الأساليب النبطية؛ التشريح.

1. Introduction

Monolithic architecture refers to a freestanding structure made of a single piece of material (Rogers, 1990). Such 'rock-cut' or 'carved-out' buildings include structures, edifices, or sculptures cut out of stone. This construction method has existed in many civilizations throughout human history, with buildings still existing, such as the Great Temple of Abu Simble in Egypt (1289 BCE), the Ellora Caves in India (600–1000 CE) and Petra in Jordan (7000 BC) (Ching, 2006; Rababeh, 2005; Fergusson, 1846). Carving out buildings is a significant cultural achievement, as sculpting monuments, tombs, habitats, and palaces worldwide. Due to the weathering resistance, the sandstone-carved-out building has survived for centuries (Grissom et al., 2020). Inherited and refined over many generations, cutting stone requires specific tools and construction strategies across many steps, including cutting, curving, and moving stone elsewhere. As (Rababeh, 2005; Rockell; 1990) claim, most carving out and stone quarry strategies start with cutting a near block or slab-shaped stone to speed up the cutting process, but not all the tools and strategies are similar.

Stone structures have been thoroughly researched: introducing computational processes coupled with advanced subtractive cutting technologies (i.e., CNC Milling, waterjet, and Diamond saw cutting) has significantly eased construction by supporting human labor through machine applications and methodologies (Clifford, 2017). Current research has developed applications for stereotomy using six-axis industrial robotic arms, with standard drills and hotwire diamond saws mounted as end effectors (McGee, 2016; Fernando et al., 2017). Other research has investigated the assembly of stone modules (Fallacara, 2016); self-holding structures (Zayas, 2017); and constructed on-site complex geometry (Johns, 2020).

While these focus mainly on stereotomy, subtractive cutting and stone assembly, this research investigates the strategy of rock cutting and carving out, including methods and tools, with the aim to enable a digital carve out, using a robot arm to achieve a comparative result. The framework of this research thus considers the end effector and the robotic kinematic, which is the study of the robotic movement of a multi-degree of freedom that forms the robotic structure system (Richard, 1981). The research explores robot reliability, accuracy, and sensibility to transfer an ancient carve out a block relying on Nabatean methods.

The present paper explores the potential of robotic subtractive fabrication for construction technologies, specifically 'carving out' space out of a solid such as sandstone or homogenous material. It reviews the Nabatean's methods and tools as a reference for carving aiming for human–robot craft transfer. Even though sandstone is one of the most used raw materials for construction purposes throughout human history, there are challenges in adapting the robot for cutting the sandstone due to uneven and unpredictable responses to a force (Shaked et al., 2021). The research simulates the experiment using an EPS foam as a homogenous material that reacts similarly to sandstone for cutting using a hotwire as a replacement for a diamond wire and a hot knife as a replacement for a circle saw. The approach is optimizing for fabrication subtractive cutting methods learning from traditional Nabatean's innovative methods, tools, and techniques. The role of automatic robotic carving can be investigated for large sandstone cutting for carving out indoor spaces and the quarrying industry.

2. Background: Carving Stone, State-of-the-art and Tradition

This section discusses precedents of implementation from traditional practice craftsmanship with hand-held manual tools, to tools attached to the robot, and potential automation; and presents an investigation on the Nabataeans carving out methods and tools.

2.1. HUMAN–ROBOT CRAFT TRANSFER AND END EFFECTOR DEVELOPMENT

In ‘Adaptive robotic stone carving: Method, tools, and experiments’, (Shaked et al., 2021) Shaked et al explore digital stonework, human-robot craft transfer, and robotic fabrication, replacing chisel and gouges in the traditional stone craft with an end effector that can apply the same skills of chisel and carving the stone. The complexity of stone carving is due to its irregular geometry, coarse texture, and unpredictable material behavior. The paper analyzes human hand gestures in action as a requirement for transferring a manual craft to a robotic subtractive carving for surface finishing and detailing. The focus is to transfer long-lasting human craftsmanship to automatic optimization to capture and analyze. A robotic sensor is applied to the end effector for unpredicted changes in the carving process.

The research methods focus on three stages: robot craft transfer, robot tools development, and experiments and validation. The methods start with testing and observing a basic chisel stroke operated by a craftsman for a complete carving session. The chisel motion is reconstructed in a 3D digital form. The motion in this case study is to test the speed of the chisel and the force applied to the stone. The research method in this study used as a guide for the human–robot transfer, the chisel implementation as a robot end effector, and the 3D documentation of the hand gesture.

In ‘Adaptive Robotic Carving: Training Methods for the Integration of Material Performances in Timber Manufacturing' 2022 Brugnaro & Hanna report on a human-robot craft transfer whereby they train a robot to resemble traditional craftsmanship in a framework of digital fabrication. While their research uses timber as homogeneous material for the experiments, the significance lies here in transferring a set of handheld traditional tools (chisel and gouges) to a robot end effector, testing sensor feedback and machine learning as methods to train the robot to replicate human skills in timber carving. The process of achieving the paper's aim starts with capturing a set of carving operations performed by a skilled human expert. Therefore, this research aims to apply the same data (i.e., force, speed, and angle) to a robot KUKA KR6 and Universal Co-bots end effector. The end effector was developed for the wood carving process based on the data and the tools from human skills in carving.

‘Digital Design to Digital Production Flank Milling with a 7-Axis CNC-Milling Robot and Parametric Design’ (Brell-Çokcan et al., 2009): In architecture, the milling process is limited by small milling due to material wastage. Brell-Cokcan et al concentrate on milling a big chunk of a material in a large-scale object in architecture using ‘flank milling’. Flank milling uses the tool's depth to carve material tangential to the surface—this exhibits several benefits with cutting large, finished object, and minimizing waste and time. A limitation, however, is that their research did not mention the material response to the flank Milling process. The prototyping uses EPS foam for the experiments as a homogeneous material. This research compares 3D milling and flank cutting in material wastage and time consumption. It results in the

effects of cutting through the material and a rough cut in both the material wastage and time.
These precedents show the implementation of handheld tools to the robot end effector as an application for robot–human craft transfer. Furthermore, the development of robotic end effectors for stone, and Styrofoam is discussed. The precedent three specifically points out the difference between 3D milling and Flank Milling as a method for less waste strategies of cutting chuck instated of milling.

2.2 THE NABATAEANS HISTORICAL METHODS

The Nabataean are considered the most advanced civilization in carving on sandstone (Rababeh, 2005). The monument's carving process must be precise, as there is no room for errors. They have used elementary, practical tools like chisel, mallet, iron picks, and crowbars. Each tool has a specific task, from carving trenches to splitting a block and refining. Their understanding of the sandstone enabled them to choose the right tools and the proper process available at that time. Then they try to split this large block out with iron picks and a mallet. The reason for carving the trenches or grooving is to space out chunk by chunk, block by block. Therefore, it is easy to move and speed up the carving process. It is a method that they used to create a space, elevation, or for stone quarries.

Figure 1. Nabateans trench cut (Rababeh, 2005).

3.3. RESEARCH GAP

While much is known about these traditional methods, this research aims to contribute to the gap between the past and the present in the context of the carving-out (rock-cut) construction technique and robotic fabrication. Consequently, the focus is on adapting the robot's ability to cut through a solid following Nabatean historical tools and strategies. By cutting a large block through or within the object to subtract from the inside out before refining or milling the details. This study

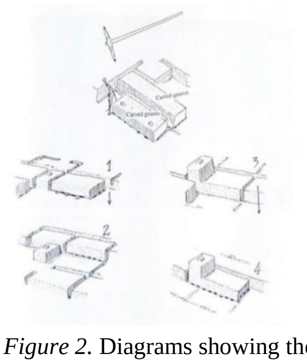

Figure 2. Diagrams showing the method of extraction a block (Korres and Bourans 1983).

examines the potential of a robot (a six-axis robotic arm) to sustain the carving out methods to create a self-holding seamless _no key joint required_ structure out of solid. It is a method to benefit not only the space that the cutting process created but also the blocks and slaps removed to be used in a different location as a strategy to minimize the waste. The research expands the knowledge of human–robot craft transfer and digital stone carving. The contribution will not be limited to reviving a traditional way to create an architectural space but to testing and studying robotic kinematics, a robotic end effector, tools, and material sensibility. The study investigates the potential to continue a local tradition of creating indoor spaces of different sizes.

3. Research Method

This research proceeds through three stages, 1) an investigation of the Nabatean's carving out methods and tools and mapping each tool and method with an equivalent method digitally; 2) manual carving documentation; and the 3) robotic transfer carving simulation and reflection of the implementation, data analysis and iterative prototyping.

3.1 THE NABATEANS CARVING OUT METHODS AND TOOLS

This project proposes to use the Nabatean's process and tools conducted to train the robot to recreate a comprehensive strategy and tools transfer (end affecter) to cut a large block of stone. The research has identified possible ways to implement similar strategies on a robot and test them: by maintaining the same invariable principles, such as a fixed location, uneven shape, and limited accessibility, the research will apply the same logic digitally. The research focused here on one phase - cutting a single block out of mass. This included creating a groove and cutting the block from the inside out using alternative yet equivalent tools, starting with a handheld tool to cut a groove and studying the hand gesture and mobility learning for the ancient technique. A customized 3D printed attachment to the robot acts as end effector to hold a carving tool. Finally, the simulation of the robot kinematic using grasshopper Kuka | PRC allows close control of the tooling path prior to cutting.

The linear diagram in Figure 3 illustrates a parallel study of carving out a solid, the trajectory of the material/stone on site to create a carved-out architectural space for the final product for both traditional and digital fabrication in the 3 phases of site planning, tools, and carving strategies. Digitally, the material mass data is transferred by 3D scanning the outer shell and cavities. Hence, the mass can be modified using CAD/CAM to create architectural space and simulate the subtractive cutting strategies. The end-effector is tested and studied before going to the last phase of the robotic comprehensive kinematics. To adapt it to the robotic cutting, and the material responsive independently for one block only as proof of the human–robot craft transfer. The linear diagram is an overall study of transferring the carving-out process, methods, and phases.

The paper reports on a select problem, i.e., carving out a single chunk out of a solid in order to test and evaluate equivalent tools to the traditional craftsman making similar impacts. Due to experiment limitations, Styrofoam (a homogenous material) is used as a substitute while maintaining the same process and logic of carving out a block. Conceptually, similar to a chisel and mallet used for carving out a trench, a 3D milling, and diamond saw can be adopted for robotic carving, and this can be simulated in Styrofoam with a hot knife can carve out trenches too. In the same way, wood wedges and crowbars - can split out a block; a wire saw can split a stone, and a hot wire can cut a Styrofoam.

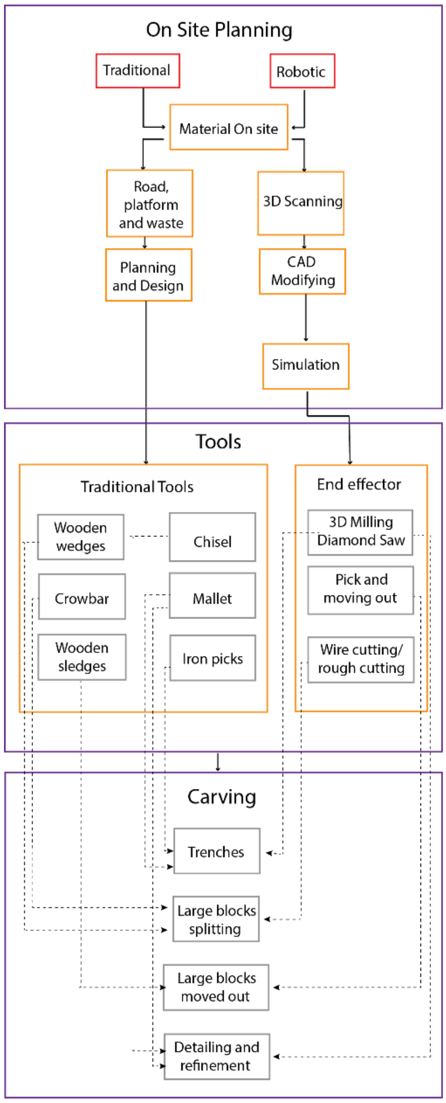

Figure 3. parallel study of the carve out building mapping.

3.2 MANUAL CARVING DOCUMENTATION

This experiment tested a basic handheld tool to identify the problems and gaps in preparing for digital transfer, learning from the hand gestures, hand speed, and rotation behavior to implement it digitally. In this experiment, handheld tools are used to carve a groove/trench to give the hotwire a space to access the solid from the inside out shown in Figure 4. The trench is created using a hot knife; there are some invariable such as the object must be in a fixed location. The handheld hot knife is limited in terms of accessibility; one access only applies the same limitation as the ancient method. In this experiment, the craftsman has no precise dimension of the depth of the tranches, as a basic measurement method has been used as the blade has been marked to identify the depth. The change in speed makes the carving with different thicknesses. However, the hand has flexibility and can rotate in many angles with a high sensibility of a spontaneous mistake's correction. Creating these trenches allows the handheld hot wire to cut from inside out a single chunk or chunks that can be reused Figure 4. Due to limitations, Styrofoam has been used as a substitute homogeneous material that can behave similarly to sandstone. In this experiment, the amount of waste was minimal. In future research, sandstones with a handheld saw will be used as a test.

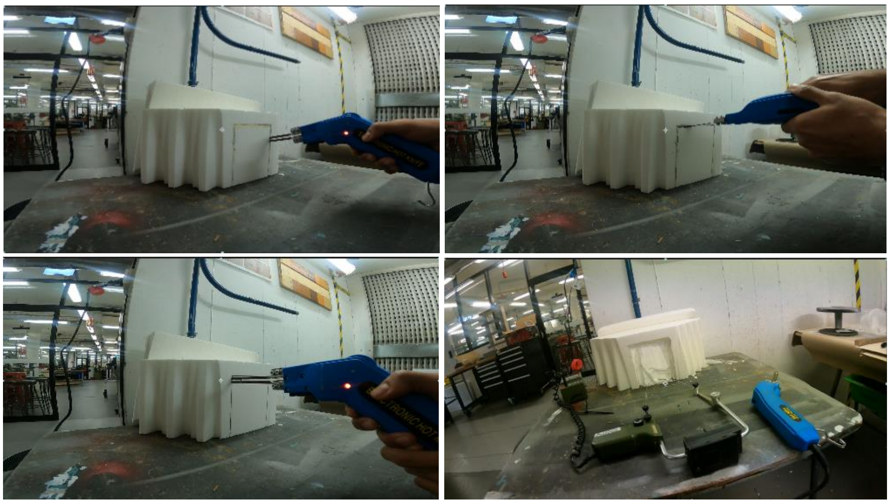

Figure 4. Manual Carving Documentation

3.3 ROBOTIC CARVING SIMULATION

In this experiment, a robotic simulation of carving trenches was conducted,
This paper adopted ancient methods and tools and the manual carving documentation to transfer the method to a digital fabrication using robotic arm. A robotic simulation was created using a grasshopper Kuka | PRC as an outcome for this experiment Figure 5. It is a simulation to test robotic resilience to cut a single-line trench. The experiment starts with a 3D model of the handheld hot knife using CAD Rhino by measuring the physical handheld tool. The 3D-modeled hot knife is attached to the robot end effector digitally. Also, an attachment must be designed to hold the knife in place for

accurate simulation. The attachments have been 3D printed to test its ability to hold the tool as a robot end effector Figure 6. As illustrated in Figure 5, the setup for the robot is attached to a table in the corner. The object/ material has been lifted off the table on the other corner. The purpose of this setup is to give the robot the space to reach the material for more accessibility see Figure 5 toolpath. The material has been lifted because of the robot's limitation of reaching the tabletop without colliding with the table or the robot body.
The simulation illustrates that the gap between the robot and the tools is getting tighter as there is insufficient space for a perpendicular cut. The simulation addressed robotic accuracy and accessibility with one access only to carve a trench. The robot simulation shows the accuracy of the robot in achieving the depth measurement of the crafted trench. However, robots cannot reach different angles as it gets closer to the material and bend with a small area inside the carved-out block. The simulation shows that the robot speeds are steadier and more consistent.

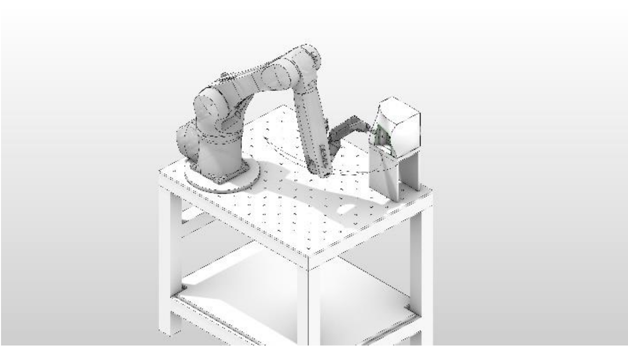

Figure 5. robotic simulation.

Figure 6. 3D printed attachment.

4. Results and Discussion

Based on the literature and the experiments, the idea of training a robot to carve out a solid as the ancient methods and tools still need to be validated as a comprehensive process. Each of the mentioned phases must be explored and tested for future research. Transferring the phase of the carve-out trench to a robot in homogenous material is an essential part of this process. Transferring a handheld tool to a robot end effector required a 3D modeling of the tools for the simulations and measurements. The robot simulation will help control the depth of the carving as a consistent cut with a steady speed, leading to maintaining the same trench size. Based on the simulation outcome:

- The robot has limitations in angles and accessibility as it collides with itself (robot body).

- The robot cannot operate a perpendicular knife cut through the object; the knife must access it from above with an angel through the object.
- The robot's future collision and mistake prediction improvement will ease this process.
- Carving out a chunk of a solid is a sustainable way to minimize waste compared to 3D milling manufacturing with a solid, as the whole chunk must be milled totally, which will take more time to produce.
- Robotic ability to cut consistent trenches by maintaining the robot speed.

The current stage of this research explored craftsmanship and how hand gestures can be translated into a robotic movement. The following research stage will explore robot movement and motion in a confined space, in line with traditional Nabatean carve-out processes.

5. Conclusion

This research outlines the potential for human-robot craft transfer in learning from Nabatean's carving tools and methods history. This research contributes to the knowledge of ancient methods of carving and implementing the ancient methods to the robotic fabrication and end effector design as novel methods for digital stonework, exploring the craftsman gestures for robot motion tracing and robotic end effector development.

The conducted experiments and simulation show the limitations of the robotic movement, as the robot does not have enough area for rotations within a small carve-out area in the carved-out material. To elaborate, the robot has a limitation to go inside the material after removing the block to carve more . The simulation identified the robot's ability to cut trenches through the material at a consistent speed from up to down. The experiments on carving out chunks with handheld tools (manually) illustrated the ability to speed up the sculpturing process, which transfers to the robot.

This research contributes to a better understanding of the affordance's limitations of digital stonework and human-robot craft transfer. Future experiments will explore the carved-out technique on site. The next stage of this project will include a robot cutting out a block with different materials—furthermore, the potential of transferring the process of a carve-out building at different scales.

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REINTERPRETING ZELLIGE TILES THROUGH CERAMIC 3D PRINTING

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Abstract. The intricate details of Zellige tile work in Islamic architecture have high cultural significance and important sacred associations. The quasi-crystalline geometry found in el Attarine Madrassa Zellige patterns are a splendid example of the geometric rigour and exceptional craftsmanship of these sacred decorations. Modern methods have been used to reproduce these complex patterns, but these methods are mostly focused on duplication, rather than contributing to the analysis and re-contextualization of these motifs. Where recent studies have investigated the tectonics and structural limitations of ceramic additive manufacturing, few have explored its unique capabilities of re-interpretation and abstraction. This paper investigates the Zellige tiles of el Attarine Madrassa in Fes through formal and tectonic prototyping via clay 3D printing. Adjustments to the pattern by twisting, shifting, and shrinking were evaluated to observe what new interpretations additive manufactured ceramics can provide to the reading of the pattern at an architecture scale. In parallel, custom tool path design strategies were developed to address the unique intersection and overlapping issues that resulted from the intricate linework of the mosaic's geometric pattern. Several full-scale physical prototypes were developed to assess the success and design opportunities of each strategy. Design iterations were also conducted to develop a key stone assembly sequence while also testing assembly tolerances and bonding between component units. Lastly, a dome mosaic assembly was designed for an arbour structure to evaluate the architectural implications of the developed tile system. The objective is for this 3D printed investigation to simultaneously honour and innovate upon the rich continuum of craft tradition, culture, embodied knowledge, and spirit within these geometries.

Keywords: *Zellige, Digital Fabrication, Architectural Ceramics*

ملخص. تتمتع التفاصيل المعقدة لبلاط الزليج في العمارة الإسلامية بأهمية ثقافية عالية وارتباطات مقدسة مهمة. تعتبر الهندسة شبه البلورية الموجودة في أنماط الزليج بمدرسة العطارين مثالا رائعا على الدقة الهندسية والحرفية الاستثنائية لهذه الزخارف المقدسة. تم استخدام الأساليب الحديثة لإعادة إنتاج هذه الأنماط المعقدة، لكن هذه الأساليب تركز في الغالب على الازدواجية، بدلاً من المساهمة في تحليل هذه العناصر وإعادة وضعها في سياقها. في حين بحثت الدراسات الحديثة في التكتونيات والقيود الهيكلية لتصنيع المواد المضافة الخزفية، فقد استكشف القليل منها قدراتها الفريدة في إعادة التفسير والتجريد. تبحث هذه الورقة في بلاط الزليج بمدرسة العطارين في فاس من خلال النماذج الأولية الرسمية والتكتونية عبر الطباعة الطينية ثلاثية الأبعاد. تم تقييم التعديلات التي تم إجراؤها على النموذج عن طريق الالتواء والتحريك والانكماش لملاحظة التفسيرات الجديدة التي يمكن أن توفرها الخزفيات المصنعة المضافة لقراءة النموذج على نطاق معماري. بالتوازي، تم تطوير إستراتيجيات تصميم مسار الأدوات المخصصة لمعالجة مشكلات التقاطع والتداخل الفريدة التي نتجت عن العمل الخطي المعقد للنمط الهندسي للفسيفساء. تم تطوير العديد من النماذج المادية واسعة النطاق لتقييم نجاح وفرص التصميم لكل استراتيجية. كما تم إجراء تكرارات التصميم لتطوير تسلسل التجميع الحجري الرئيسي مع اختبار أيضًا تفاوتات التجميع والترابط بين الوحدات المكونة. وأخيرًا، تم تصميم مجموعة فسيفساء مقببة لهيكل الشجرة لتقييم الآثار المعمارية لنظام البلاط المتطور. الهدف هو أن يقوم هذا التحقيق المطبوع ثلاثي الأبعاد بتكريم وابتكار السلسلة الغنية من التقاليد الحرفية والثقافة والمعرفة المتجسدة والروح في هذه الأشكال الهندسية.

الكلمات المفتاحية: *زليجى، التصنيع الرقمى، صناعة الخزف المعمارية.*

1. Introduction

Within Islamic architecture, ornamental tile work is a feature that has deep cultural and historical significance, as well as important sacred associations (Burckhardt, 2001). The patterns symbolize spiritual devotion and unity with the divine (Chaabani, n.d; Damluji and Hedgecoe, 1992; Thalal *et al*., 2011) so they are commonly found in prominent public and religious spaces, such as masjids and madrassas. The patterns found in el Attarine Madrassa's Zellige panels are a great example of the high level of geometric rigour and exceptional craftsmanship of these sacred decorations (Aboufadil, Thalal and Elidrissi, 2013; Aboufadil, Thalal and Raghni, 2013; Burckhardt, 2001; Damluji and Hedgecoe, 1992). This paper investigates the Zellige tiles of el Attarine Madrassa in Fes through clay 3D printing. The analysis looks at formal and tectonic investigations of the tiles complex geometry while offering suitable methods for their fabrication.

Figure 1: The entrance to the prayer hall of el Attarine Madrassa in Fes, from the courtyard. Image by authors.

The Zellige tile pattern decorates either side of the archway opening separating the courtyard and the prayer hall of el Attarine Madrassa. The madrassa's ground subtly steps up, highly articulated stucco muqarnas wrap above, and to either side lies this Zellige panel (Fig. 1). This quasi-periodic panel, with its complex mathematical ingenuity, interrupts the otherwise simple periodic tiling within the courtyard (Fig. 2). Aboufadil et al.'s research (Aboufadil, Thalal and Elidrissi, 2013) highlights this complexity, when they note the panels' perfect similarity to the diffraction patterns observed in naturally formed quasicrystals of aluminum alloys. The tiling, classified as a fivefold quasiperiodic symmetry, much like the Penrose tiling (Aboufadil, Thalal and Elidrissi, 2013), can tile a surface infinitely without ever repeating. This type of symmetry relies on an origin, about which the pattern is rotationally symmetrical. The complex and mesmerizing patterns of these tiles have captivated the imagination of scholars and artists alike through their mathematical precision and beauty.

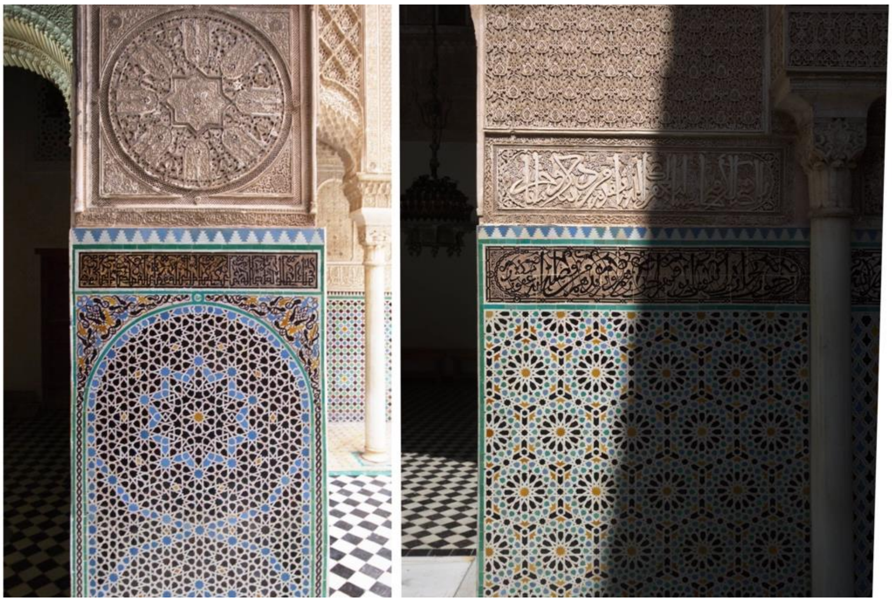

Figure 2: Panels from the courtyard prayer hall entrance of el Attarine Madrassa. Left: The fivefold, quasiperiodic, rotational symmetry of the panel of interest. Right: The sixfold, periodic, translational symmetry of the panel around the corner. Image by authors.

Modern methods have been used to copy and reproduce these complex patterns, but these methods are mostly focused on duplication, rather than contributing to the analysis and re-contextualization of these motifs. For example, while the Louvre Abu Dhabi, designed by Jean Nouvel (2017), took inspiration from the geometric complexity of Islamic tile work, the project focused on its application as a shading device rather than investigating the pattern itself. Contemporary architectural ceramic research typically aims to produce homogenous components that can be replicated to suit a variety of architectural and industrial applications such as bricks or tiles (Bechthold et al., 2015). Where recent studies have investigated the tectonics and structural limitations of ceramic additive manufacturing at various scales (Ochoa, 2021; Shi et al., 2019), few have explored its unique capabilities of re-interpretation and abstraction. This research deviates from these conventions of ceramic fabrication that encourage regularised performance attributes. Instead, the research uses the plastic deformation tendencies of clay and additive manufacturing to re-create and re-contextualize these sacred geometries with varied visual results not achievable through alternative production processes.

2. Research Context

Liquid Deposition Modelling (LDM) is a form of ceramic 3D printing which is low-cost and utilizes clay bodies without any additional support material or formwork (Gürsoy, 2018). Self-supporting forms are made possible by clay's plasticity, and tensile strength properties (Clarke-Hicks, 2021). However, the viscoelastic nature of the material being deposited results in a discrepancy between the digital model and the 3D printed result. While LDM can be compared to Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) printing, in that it creates printed parts with direction-dependant properties (Ahn et al., 2002), LDM can result in unpredictable plastic deformation when 3D printing complex geometries (Gürsoy, 2018). The liquid characteristics of clay are in full effect when addressing overhang angles in the geometry. When the extruder deposits over an unsupported overhang path, a sagging coil forms with a distinct aesthetic appearance. These phenomena have been previously used to create ornamental 'loops' in clay (Rael and San Fratello, 2018; Shi et al., 2019). While these behaviours can be considered undesirable for structural applications, they can also be harnessed to address performance characteristics such as light translucency (Clarke-Hicks et al., 2022).

The presented research also builds on previous literature on computational methods to manipulate toolpaths (García Cuevas and Pugliese, 2020) as well as additional investigations on materials carried out by other researchers. AlOthamn et al. (2019) proposes a method of clay printing that deviates from the typical 3D printing process of successively depositing planar layers of material atop one another. This was achieved by modelling in adjusted toolpaths which work to anchor, drag, and pull the clay at the nozzle to allow for self-supporting clay loops. Ko et al. (2019) as well as Dunn et al. (2016) similarly overcame the limitations of conventional slicer toolpaths to print non-planar ceramics in curved moulds. In these cases, a break away from the conventional deposition methodology was essential for manufacturing a free-form artifact. Rosenwasser et al. (2017) as well as Friedman (2014) successfully deployed a method of customizing toolpaths to allow the deposited clay to imitate hand-woven string by overlapping 2 crossing toolpath layers.

By providing a 3D printing workflow for generating the digital model as slices without the use of slicing software, the research presented in this paper demonstrates a controlled method to designing 3D printed clay tiles with a complex geometry. Tool path design and the material's fluid characteristics are utilized complementarily to intentionally present the geometry in a novel way.

3. Methods

3.1. PRINTER

A Potterbot XLS-1 SCARA type 3D printer with a 3600cc syringe extrusion system and a 4.0 mm circular nozzle was used for all the prints. Clay was loaded into the print cartridges via a 4" wall-mounted extruder, to remove air pockets and homogenize the clay consistency. Since the accumulated pressure required to extrude clay with the large syringe extruder leads to a ten-second delay in the extrusion function, resulting in unwanted oozing of clay, all prototypes are designed as one continuous printed coil.

3.2. CLAY

The clay used for this research was PSH-516, which is a cone 6 stoneware. This clay was selected due to its good light reflection properties. High Kaolin and Nepheline Syenite in PSH-516 provide it with a neutral white appearance at the mid-range firing temperatures, as well as ideal firing properties. Feldspar and silica are 2 components that help mitigate any lost plasticity during wet processing resulting from the other components and promote vitrification during firing.

Water was added to the clay at a weight ratio of 1:40 (Clarke-Hicks et al., 2022). The aim for the addition of water was to promote the viscid properties of the clay, which is needed for easy extrusion. Water content has an impact on the print behaviour itself; too little water will cause the print layer to delaminate due to low adhesion and will also demand more torque from the machine to extrude. This could lead to clogging the nozzle or burning out the motor. Too much water, on the other hand, leads to very liquid clay and may lead to the collapse of the print.

3.3. TOOLPATH DESIGN

Alternating toolpath layers were generated as polylines in Rhinoceros, extruded into individual layer surfaces, then exported to G-code using Simplify3D (Fig. 3).

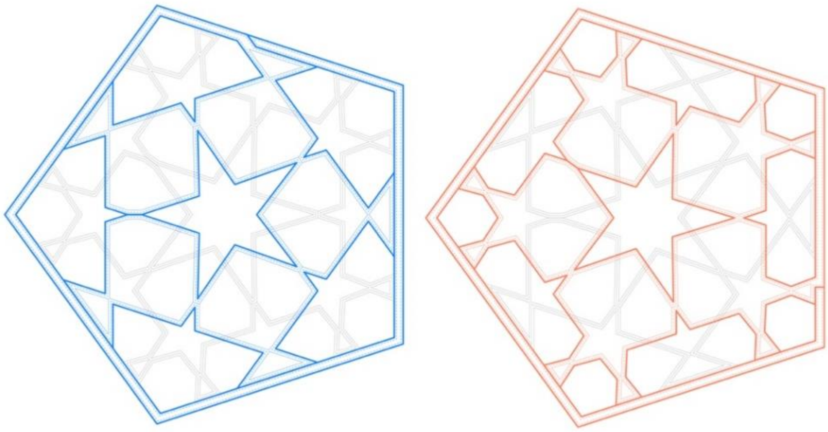

Figure 3: Simulation of toolpath divided into 2 alternating layers.

3.4. SLICER PRINT SETTINGS

The inputted parameters into the slicer are outlined here. A 1-inch skirt was used to start the print and establish the flow of the material. Continuous stepping was enabled, with a G-code step height of 2mm to match the digital model and maintain a consistent stepping. A 2mm nozzle diameter was used to allow for clay intersection at desirable points. Lastly, the extrusion Multiplier was set to 10 (to compensate for the smaller nozzle diameter setting.

4. Results

4.1. TILE PATTERN TRANSLATION INTO PRINTING PATH

The first test used an initial tile pattern to evaluate the print path development workflow. The toolpath for the extracted pattern relied on many points of self-intersection, which due to the viscoelastic nature of the clay would cause the pattern to instantly deform. This is because the nozzle would push the previously deposited clay out of its original position. To alleviate this challenge, and to allow the digital model to be read correctly by the slicer software, the pattern was split into two alternating layers (Fig. 4). This resolved the issue, as it would allow the upper layer to weave over the lower one, with each layer being its own closed loop. Each pair of layers was then extruded to the same height as one printed layer of clay, 4mm. The printing of two stacked layers resulted in the completion of the original extracted pattern.

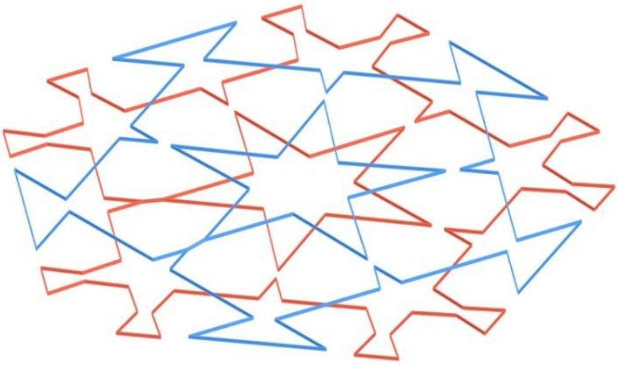

Figure 4. Diagram of the two overlapping layers that comprise the full pattern.

Due to the pattern's multitude of overlapping lines, the dissection of the geometry became an issue that required the individual design of the print pattern. At the time of experimentation, there was no direct computational method to translate a given geometry into two working toolpaths. As a result, a manual process of splitting the pattern took place to eliminate self-intersections on the same layer (Fig. 5). The pattern only needed to be separated once for each tile design. How the pattern was split became an iterative workflow that was streamlined with the fabrication process.

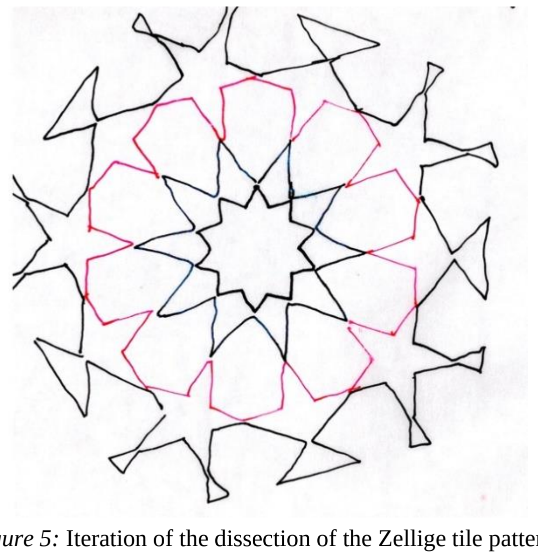

Figure 5: Iteration of the dissection of the Zellige tile pattern.

4.2. TILE PERIMETER

The addition of a perimeter print path was essential for the print to remain flat, as without the border, a significant degree of warping was observed as the clay dried. Though the border resolved the warping (Fig. 6), an additional challenge was revealed, as to remain closed, the toolpath had to draw much of the perimeter twice. This resulted in perimeter walls becoming twice as thick as the interior walls of the tile. An insulating effect was observed, where the thicker outer border dried faster, leaving the thinner clay on the inside unable to shrink and contract freely, causing it to crack (Fig. 7). To mitigate this issue, the tool paths were adjusted to minimize the overall border thickness, while retaining a complete border.

Figure 6: After firing corners of the print are lifting from the table due to warp.

Figure 7: Cracks observed in interior walls of 'shrinking' prototype print, caused by differential thickness and drying time between interior and perimeter walls.

The prototypes dried in moisture-controlled chambers over approximately 7 days to minimize risk of warping and delamination. During the drying stage, an air gap was ensured via wooden blocking in between stacked tiles to allow more consistent air flow and drying to both the exterior and interior walls of the clay.

4.3. GEOMETRIC MANIPULATION

Throughout the experimentation process, the goal was to explore the capabilities of machine printed clay and its unique ability to create geometries that are otherwise difficult to fabricate. Four key geometric manipulations were used to investigate the pattern, each categorized by a different transformation; twisting, shifting, shrinking, and slumping (Fig. 8). Each was varied and examined through physical prototypes. Visually documented information from these processes informed alterations to the input amounts as well as toolpath spacing for subsequent design iterations. After a total of 20 iterations, one transformation category was selected to be further developed and applied into an architectural dome assembly.

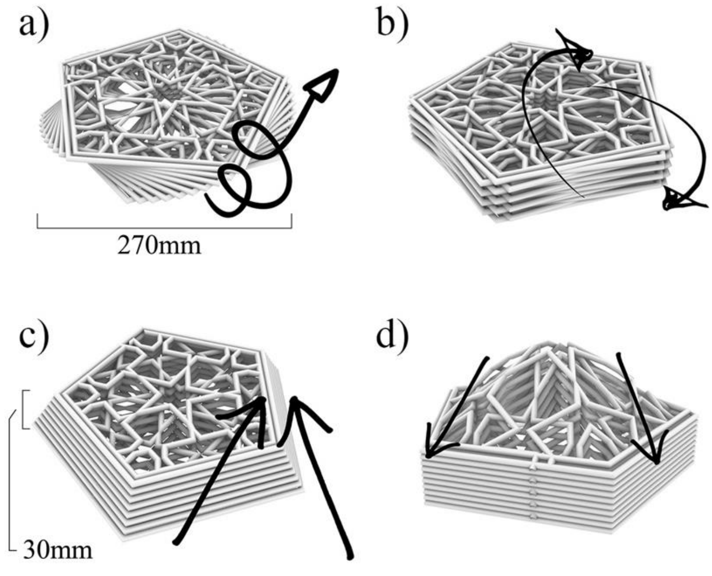

Figure 8: Pattern transformations a) twisting, 3 variations, see below. b) shifting, c) shrinking, 3 variations, see below. d) slumping. Tiles measured 270mm in diameter and 30mm in height.

4.3.1. Twisting

The base Zellige tile pattern with a simple pentagonal border was altered via twisting. Each layer was progressively rotated relative to the centre by a fixed increment. Different increments of 0.5-degrees, 1-degree and 2-degrees of rotation were tested, with varying results for each (Fig. 9).

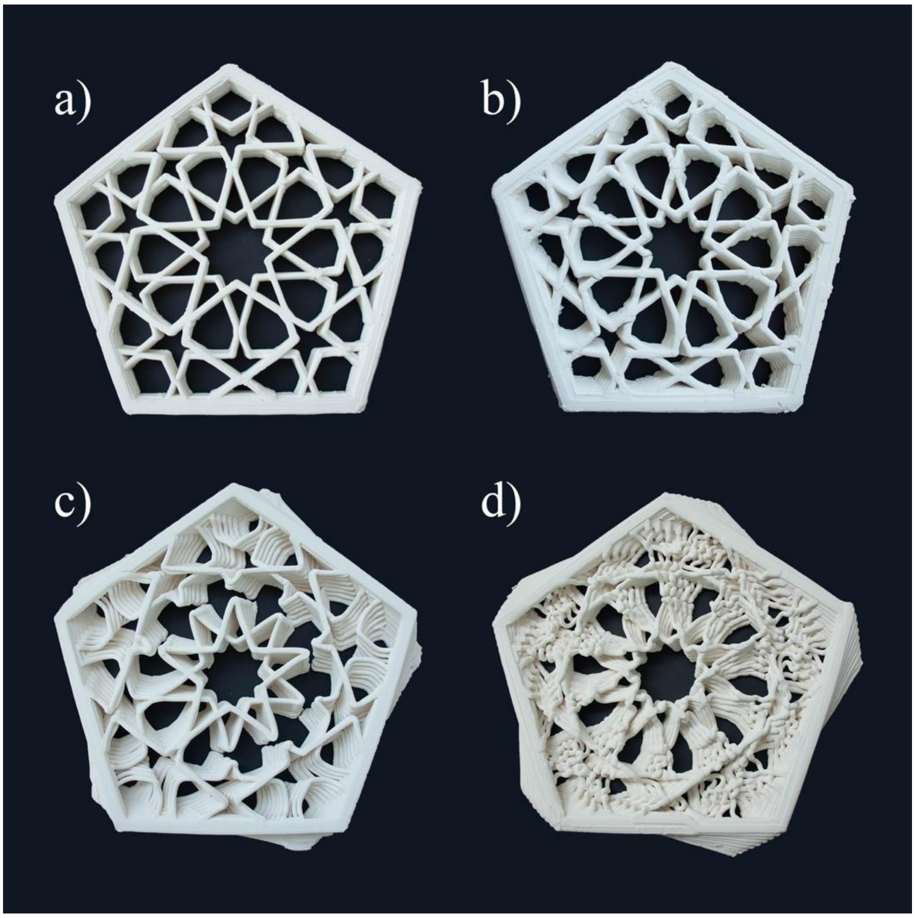

Figure 9: Twisting test prints, a) 0-degrees twist, b) 0.5-degrees twist, c) 1-degrees twist, d) 2-degrees twist.

The lowest amount of rotation, 0.5-degrees, displayed a very slight reduction of porosity, with no visible deformation to the pattern, whereas the largest amount of rotation, 2-degrees, displayed a significant reduction of porosity. As the amount of rotation increased, deformation of the pattern occurred due to low vertical alignment between layers. A visual effect occurred, where both aperture reduction and deformation were minimal near the centre, but exponentially more potent towards the outer pattern border.

4.3.2. Shifting

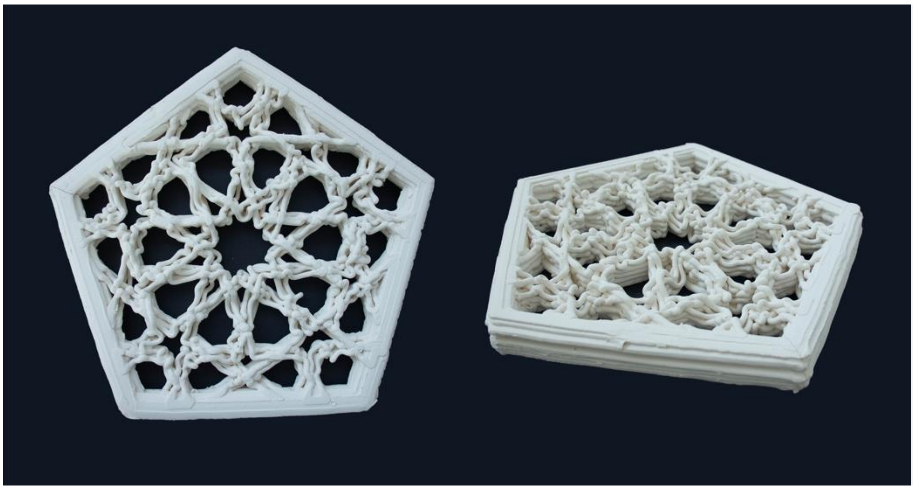

Figure 10: Shifting test print, alternating layers were shifted 5-degrees clockwise and counterclockwise about the centre.

The shifting option also featured rotation of the layers relative to the centre, though the rotations were more dramatic. As the full pattern is completed within two layers, the second layer is rotated 5-degrees counterclockwise about the centre point. Then for the next pair, the second layer is rotated 5-degrees clockwise. This pattern is then repeated for the remainder of the print (Fig. 10).

The shifting has an immediate effect on the aperture and porosity reduction of the tile, however with this case, the reduction was limited to the amount of shift, and not the number of layers. With transformations such as twisting, it would be possible to make the tile nearly opaque simply by adding more layers. Though the lines were less clean when the shifting was applied, the pattern remained moderately legible compared to the 5-degree twist. Unlike the twisting prototypes which had less deformation in the centre, and more towards the outside, deformation with shifting was consistent throughout (Fig. 10).

4.3.3. Shrinking

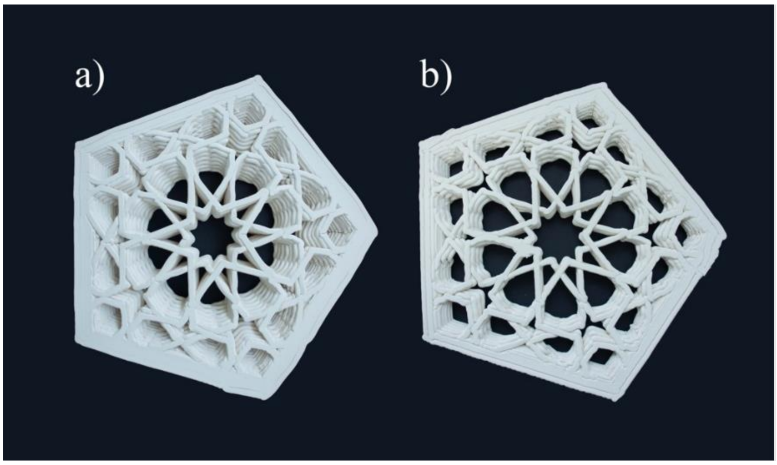

Figure 11: Shrinking test prints, bottom view. a) 1% shrinkage, b) 2% shrinkage.

For shrinking, each layer was uniformly scaled down relative to the bottom-most layer, tapered towards the centre. Prototype iterations of the base pattern were printed at 1%, 1.5%, and 2% shrinkage (Fig. 11).

The shrinking transformation provides an almost negligible impact on aperture reduction near the centre of the pattern, whereas the outer pattern was impacted heavily. The same was true for deformation, as most of the looping effect due to layer misalignment was observed in the outer pattern. Continuity of lines and pattern legibility remained strong from 1% shrinkage to 1.5%, and the geometric pattern was more legible and visually engaging than the twisting transformations.

4.3.4. Slumping

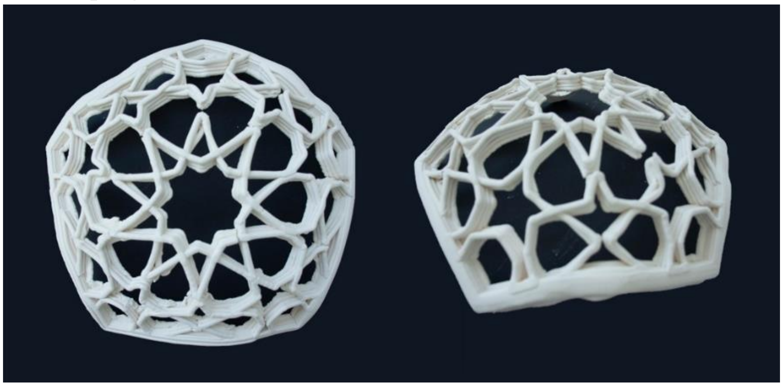

Figure 12: Slumping test print.

Slumping of the pattern to achieve distortions in the z-axis was also tested by printing on a piece of fabric and then lifting and laying the fabric onto the round surface of a standard soccer ball.

The slump experiment revealed that for the instances where two edges which meet at an angle but do not intersect, the distance must be no more than 4.5mm apart to allow for a strong bond. When there was no adhesion between these two points in the prototype, the slumping process exaggerated the gap, compromising the patterns continuity and structural integrity (Fig. 12).

Although all experiments yielded fascinating iterations of the pattern, the shrinking pattern was chosen to be further developed, primarily due to its aggregation potential. The tapered edge profile provided from the shrinking pattern allowed for the pieces to be treated as keystones in a larger dome aggregation, an architectural artefact. The dome application was particularly beneficial as it allowed the final artefact to stay true to the original pattern, radiating outwardly from a single centre and extending infinitely outwards.

4.4. DOME ASSEMBLY

To test the interaction between tiles, a dome aggregation was explored. Discrete shapes were generated, maintaining the logic of the pattern. This was done by referencing one of the methods in which Zellige masters traditionally generated patterns, subdivision (Lu and Steinhardt, 2007). In this method, the craftsman began by identifying the intended symmetry, in this case, a fivefold symmetry. Next, they took a basic fivefold pattern, often a rosette, subdividing it repeatedly until revealing the desired level of detail (Lu and Steinhardt, 2007). In this research, the symmetry of the pattern and its generation process are revealed and reinterpreted through modern means, highlighting the craftsmen's impressive undertaking.

The pattern's discrete centre was the starting point to creating the simplified components for printing. Looking at the centre of the pattern, the root rosette of the pattern was identified (this would also be where the permutations of subdivision would have stopped). A complex Zellige pattern is always based on an aggregation of rosettes, although in the case of a fivefold symmetry such as this, specific local manipulations are required (Youssef Aboufadil et al., 2013). The geometry of the root rosette was scaled up to reveal the potential start point of a subdivision – this can be seen when the lines of the scaled-up rosette match the lines of the pattern itself (Fig. 13). From there, the scaled-up rosette was simplified, to limit the number of unique components, the number of joints between each component, and to simplify the overall geometry of each shape. This was done for the sake of constructability.

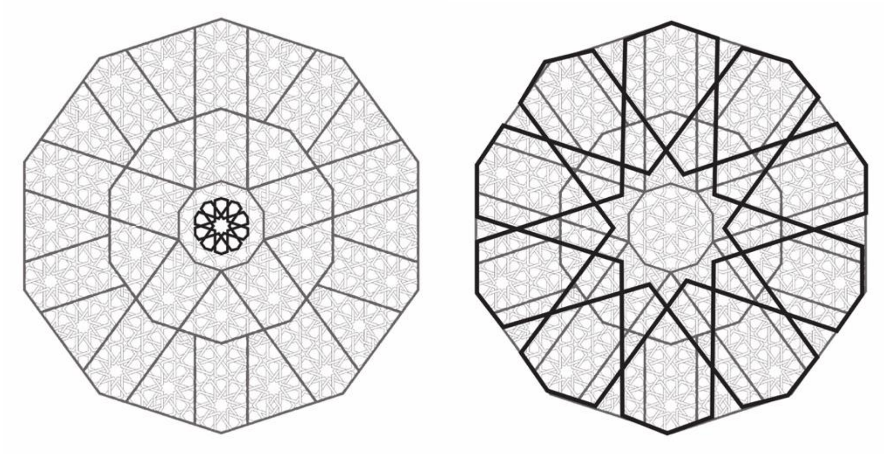

Figure 13: Rosette overlayed with division of geometry.

The method of dividing the toolpath into 2 alternating layers was applied to each subsection of the pattern, and new borders were drawn accordingly. Iterative modifications were made to the digital toolpath at the borders, to reduce the number of redundant overlaps per layer. This in turn reduced overall border thickness and ensured greater visual continuity of the larger pattern. (Figure 14).

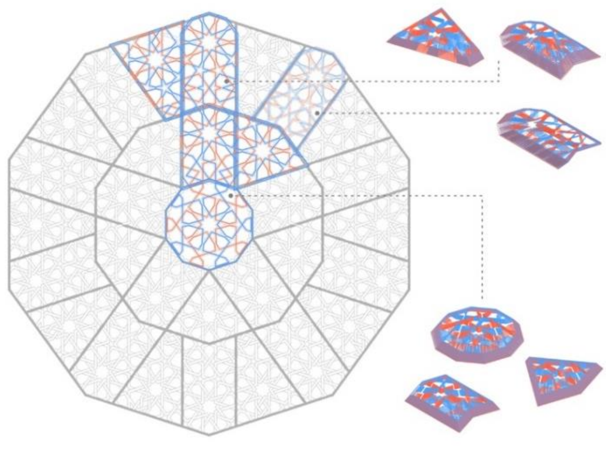

Figure 14: Toolpath applied to larger pattern and individual components.

The width of the kiln shelf was the limiting factor for the size of any given piece. Working in conjunction with the simplified shapes, in a digital model, the final sizes of the pieces and the shallowness of the dome was determined. The desire was for a subtle curvature, such that the flatness of the pieces was not disruptive from the reading of the overall structure as a smooth dome, rather than a faceted one.

With the discrete components and their sizes determined, the orientation and shrink percentage of each component were determined next, so that their aggregation would yield the desired curved keystone effect. After experimentation, 2% was determined as the maximum percentage of shrinkage for the density of the pattern at the intended scale. At 3% shrinkage, the pattern deformed significantly, resulting in a highly abstracted version of the pattern, which was deemed undesirable. At 2%, there was just enough alignment between layers in the x/y axis to support the successive layer, maintaining the integrity of the pattern with a controlled abstraction (Fig. 11). The pattern could deform in specific areas of each print, maintaining the integrity of the overall pattern, while highlighting the elastic qualities of the clay, and hinting at the process of its creation via robotic extruder. 1% shrinkage was determined as the minimum, as 0.5% shrinkage displayed negligible deformation. There was also insufficient visual difference between 1.5% and 2% shrinkage.

The final dome consists of 6 different prints shrinking at 1%, and 2% (Fig. 15). Through iterations in the digital model, it was decided to start with the Centrepiece (C) at 2%, shrinking inwards. From there, Arrow-Inner (AI) was set to 1% shrinkage outwards. The joint between C and AI, 2% in and 1% out yielded the desired curvature. With this logic, Kite-Inner (KI) would shrink at 2% in, and so on for the outer ring. Given that the outer ring introduces 3 shapes that all meet one edge (KO, AO, KO meeting the edge of KI), the logic of the method of alternating 1% and 2% was broken, and a specific local manipulation was required. In this case, the decision was to create a unique AO piece – AO1 – where the V-shaped edge meeting KI was shrinking at 1% out, while the rest of the shape maintained its shrinking of 2% in. This meant that instead of five unique components, there were six. Upon reflection, this break in the otherwise sound logic method is a by-product of the complex quasiperiodic nature of the pattern, and another point of homage to the designers of the original Zellige pattern, who would have also had to manipulate the pattern in ways not required by a regularly periodic pattern.

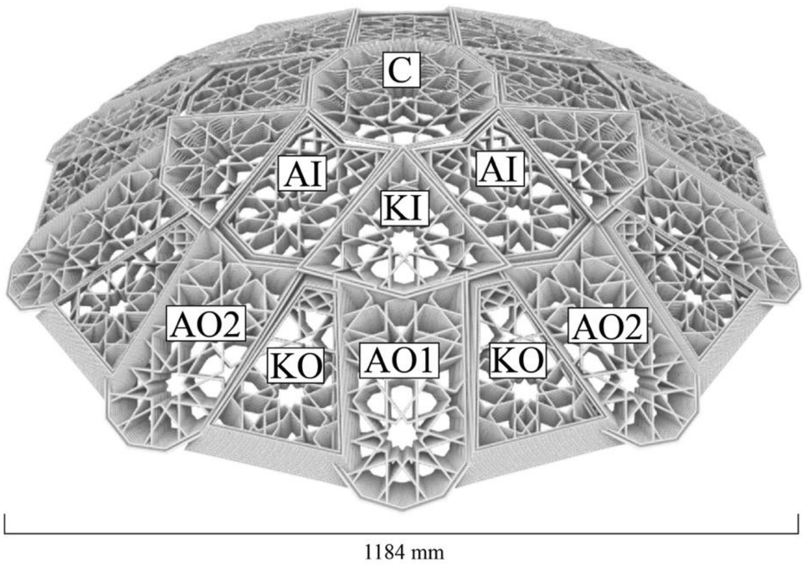

Figure 15: Digital model of complete dome, noting each unique tile. The dome has a diameter of 1184mm, and a height of 203mm.

5. Discussion

During the development of the toolpath for these test prints, it became evident that the tile pattern was not suitable for a standard slicer workflow. An understanding of the software's method of converting a digital model into a G-code toolpath allowed for manual slicing of the prototype model into alternating extruded closed polylines. It was observed that high cross-sectional variation between paired layers of clay quickly resulted in high plastic deformation, and in turn caused the base geometric pattern to distort.

The process of splitting the pattern allowed for an emergence of new geometries, while at the same time generating a deeper understanding and appreciation of the complexity of the geometry. Not only that, this method of analysis and re-interpretation can also be applied to a variety of traditional patterns across cultures. In facing the challenges of printing a pattern, the inherent intricacies of the geometry are revealed, and traditional patterns reinvigorated. The quasi-periodic pattern is explored further with searching for multiple ways of subdivision. The investigation into this unique combination of artistry and contemporary fabrication methods prompts many future research avenues.

Further experimentation and analysis can be conducted to reduce cracking in individual pieces. The complex pattern resulted in multiple interior walls when typical printed clay forms only had at most two. Difficulties arose in the drying process as the clay dried at different rates causing the cracking. Strategies for crack prevention were unexplored within the project and could benefit from additional research.

In each of the four geometric manipulations: twisting, shifting, shrinking, and slumping, a new reading of the pattern emerged, allowing for a relaxation of the pattern. The plasticity of the extruded clay filament became evident in the twisting and shifting iteration especially. Readings of this culturally and spiritually significant pattern become 'fuzzy'. There is an implied lack of control despite parameters being tightly controlled.

The non-figural traditions of Islamic ornamentation were stripped to pure geometry in the Zellige panels of Morocco, where the representation of God and holiness were reinterpreted as complex mathematical patterns. This research presents an added dimension of richness in the same non-figural tradition. The implications of this research for Islamic and Moroccan architecture of the 21st century are vast, as it proposes methods for generating new forms for culturally and religiously significant patterns.

The site of the final dome is proposed to be in the Islamic paradise gardens (Fig. 16). Figure 16 shows the union of contemporary architectural fabrication methods with the rich artistic heritage of the Islamic world. As an arbour resting above the fountain, the Zellige tile pattern is reflected above and below. The tile pattern at the feet of the visitor is extended to the canopy above, while there is a play of light and shadow cast by the arbour on to the fountain itself - another important symbol in the Islamic courtyard. Layers of the pattern presents itself everywhere, resonating deeper with the motifs of unity, order, and divine beauty.

Figure 16: Rendering of dome in paradise garden. Composite image by authors.

Light, in Islam, is a symbol for truth, knowledge, and eternality. Many of the rich Islamic geometric patterns which are seen in Zellige tile patterns, are also seen in stained glass windows and *mashrabiya* screens throughout Muslim architecture.
However, both stained glass windows and *mashribiya* screens (like the Zellige panels) are 2-dimensional applications where light simply passes through. The contribution that this research presents is a way to capture light through the interplay between the shrinking clay layers, and the overall 3-dimensional form of the dome. The dynamic forms possible through methods such as the ones presented for 3D printed clay can create novel formal applications for this previously 2-dimensional pattern to capture light (Fig. 17).

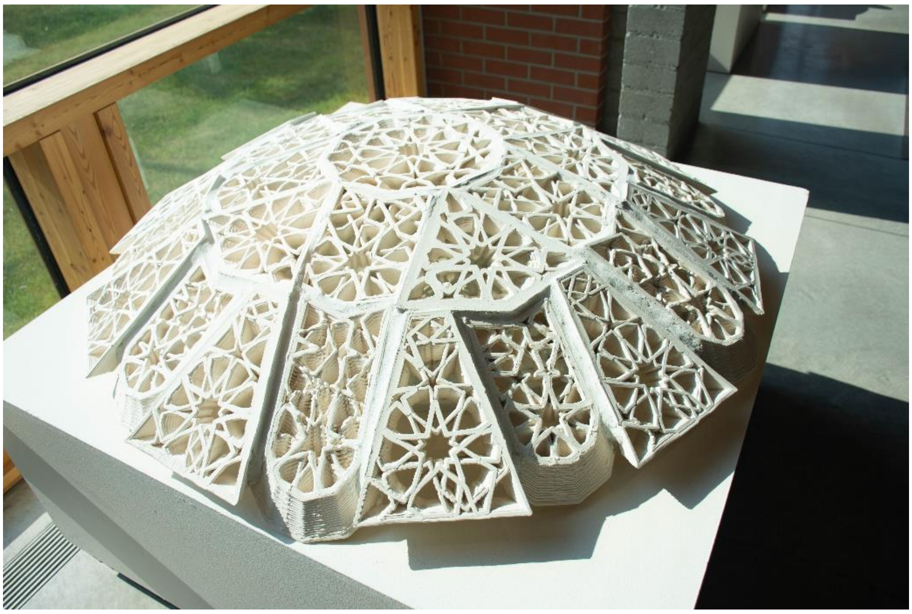

Figure 17: Completed dome with all pieces of the pattern.

By harnessing the potential of ceramic additive manufacturing, the boundaries of creativity can be pushed to contribute to the ongoing dialogue surrounding the historical and cultural significance of these motifs. This research presents a new way to look at the complex Zellige tile patterns of Moroccan madrassas. The craft of Zellige is slowly diminishing, as fewer artisans remain, and newer generations turn away from the craft. By re-interpreting the craft through the medium of clay 3D printing, not only is there potential for new applications of these patterns through modern methods, such as the ones presented here, but the traditional craft of Zellige, as practiced for hundreds of years, is itself rejuvenated through the discourse. Thus, prolonging the craft of Zellige and allowing it to live on, both in its traditional, original form, and in the form of modern reinterpretations, into the future of the architecture and design field.

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USABILITY OF PARAMETRIC DESIGN PLUG-INS AS A SUPPORT TOOL IN URBANISM AND CIM

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Abstract. The rapid growth of medium and large cities has led to an increasing demand for innovative and intelligent solutions for urban design and infrastructure. The use of City Information Modeling (CIM) and parametric design software has been one of the implemented solutions, allowing for greater agility in the process and integration with databases to recreate a digital urban structure and simulate complex scenarios. However, many of these tools remain relatively unknown among urban designers, with plenty of potential to be explored. This research aimed to identify the recent practices in the use of algorithmic-parametric design at the urban scale and in CIM project management, and explore their applications through a systematic review of the literature based on scientific articles. The review resulted 37 articles that were selected for a detailed search in the abstracts, methodologies, results, and discussions. The most frequently employed tools are related to urban energy efficiency, traffic planning and walkability, urban morphology analysis, and building typologies and density. Algorithmic-parametric design applications and plug-ins were identified to assist mainly in flow analysis, performance, comfort, and city modeling. Additionally, 23 statistical and geographic database formats were identified that generate volumes and land and mass spaces or perform performance analysis data processing.

Keywords: *Urban design, CIM, Parametric design, Plug-in.*

ملخص. لقد أدى النمو السريع للمدن المتوسطة والكبيرة إلى زيادة الطلب على الحلول المبتكرة والذكية للتصميم الحضري والبنية التحتية. وقد كان استخدام نمذجة معلومات المدينة (CIM) وبرامج التصميم البارامترية أحد الحلول المنفذة، مما يسمح بمزيد من المرونة في العملية والتكامل مع قواعد البيانات لإعادة إنشاء هيكل حضري رقمي ومحاكاة السيناريوهات المعقدة. ومع ذلك، لا تزال العديد من هذه الأدوات غير معروفة نسبيًا بين المصممين الحضريين، مع وجود الكثير من الإمكانات التي يمكن استكشافها. يهدف هذا البحث إلى التعرف على الممارسات الحديثة في استخدام التصميم الخوارزمي البارامتري

على المستوى الحضري وفي إدارة مشاريع CIM، واستكشاف تطبيقاتها من خلال مراجعة منهجية للأدبيات المبنية على المقالات العلمية. نتج عن المراجعة 37 مقالة تم اختيارها لإجراء بحث تفصيلي في الملخصات والمنهجيات والنتائج والمناقشات. ترتبط الأدوات الأكثر استخدامًا بكفاءة الطاقة في المناطق الحضرية، وتخطيط حركة المرور وإمكانية المشي، وتحليل المورفولوجيا الحضرية، وأنواع البناء وكثافته. تم تحديد تطبيقات التصميم الخوارزمي البارامتري والمكونات الإضافية للمساعدة بشكل أساسي في تحليل التدفق والأداء والراحة ونمذجة المدينة. بالإضافة إلى ذلك، تم تحديد 23 تنسيقًا لقاعدة البيانات الإحصائية والجغرافية التي تولد الأحجام والمساحات الأرضية والكتلة أو تقوم بمعالجة بيانات تحليل الأداء.

الكلمات المفتاحية: *تصميم حضرى، نمذجة معلومات المدينة، التصميم البارامترى، إضافات برمجية.*

1. Introduction

Algorithmic-parametric programming systems have gained ground in all sectors of modeling of Civil, Structural and Architecture (CSA) projects, and have also offered applications in the urban planning of infrastructure and energy consumption. Consequently, the search for professionals and specialized tools has a growing trend, since these applications have the potential to apply parametric functions capable of working efficiently with the large volumes of data that a model of a city or urban section requires. The urban design category is usually governed by the design guidelines established by the public administration, which can be seen as a potential stakeholder in pursuing urban modeling applications. It is important to note that the design tools used by government administrations may have not yet adequately kept pace with territorial and urban infrastructure expansion, and this exposes a global insufficiency of human, technological and legislative resources, which need to be improved to deal more efficiently with the challenges of contemporary urban planning (ALMEIDA; ANDRADE, 2018).

Wang et al. (2020) suggests that cities should be treated as devices, and that they can be managed from systems such as CIM (City Information Modeling), which allow designing and improving the city through processes in integrated and interdisciplinary models. The concept of CIM models, according to Stojanovski (2013), refers to an analogy of association between a BIM (Building Information Modeling) model and a GIS (Geographic Information System) model, with a purpose of unifying and crossing statistical and constructive data of the city in a collaborative database. This process involves steps such as the concentration of urban data in structured databases, with a subsequent investigation of the possibilities of using tools and plug-ins, and it may often be necessary to associate these data with parametric design tools for more flexible analyzis and new perspectives of solutions through simulations in the urban space.

Such integration should enable the processing of extracted data out of statistical relationships, such as traffic congestion, or directly from the citizen's experience, such as flow or environmental comfort. These data sets can be processed to generate performance simulations of certain regions of the city or clusters of buildings, which would be unfeasible for a designer to perform manually. These parametric analyzis are capable of generating projections of a number of possible solutions that can assist in decision making for future interventions and planning (THOMPSON et al., 2016; DALL'O, ZICHI, TORRI, 2020).

Lima (2017) explains that the use of parametric design tools is still relatively new in the urban design and planning process, and it is not yet widespread in offices in the area of urban planning. However, new parametric design technologies are emerging and are gradually gaining adoption in the large-scale urban design sector, since it enables the development of tailored solutions that align with the unique requirements of each city, considering factors such as climatic conditions, acoustic comfort and budgetary constraints (STEINØ; VEIRUM, 2005).

The term "algorithmic-parametric logic" is treated by Lima (2017) as an association between algorithmic logic and parametric modeling. This approach suggests the deepening of Visual Programming Languages (VPL) to provide greater effectiveness to the resources of parametric tools. In this process, the initial step involves the breakdown of algorithmic-parametric logic and project data through a theoretical review and computational modeling. In the following steps, textual instructions must be defined to generate a solution to a proposed problem, with subsequent conversion of these instructions into the parametric language, enabling different parts of the model to relate and modify together in a coordinated manner. This type of modeling brings a change in traditional modeling concepts, since the functions and their variables can later be understood in their entirety by any professional who has mastery of the VPL, thereby leaving an "inheritance" of information from the design process left by the project creator, which is beneficial while collaborating within a team (LIMA, COSTA, ROSA, 2020).

Based on this scenario of constant emergence of new applications, it is proposed to carry out research aiming to identify the recent practices of the use of parametric design in complementary analyzis to urban planning and CIM projects by designers such as architects, engineers and urban planners involved in the management of planning and analysis of the city and its infrastructure.

2. Methodology

The methodological process involved conducting a systematic review of the literature, encompassing scientific articles to identify the predominant use of parametric design applications by designers. To achieve this objective, three internationally recognized databases were employed, namely 'Cumincad,' which compiles important journals focused on the technology of architectural and urban planning projects, 'Science Direct' and 'MDPI,' which house journals related to technology and innovation. To obtain updated technology data, the time range of the research was defined as from 2019 to 2023, and the criteria for selecting articles were the choice of projects and analyzis at the city scale or urban clippings, and that make use of algorithmic-parametric modeling applications and plug-ins with languages in English, Portuguese and Spanish. The strings "parametric design", "City Information Modeling" and "Urban" were searched, as described in Table 1.

TABLE 1. Articles analyzed (Source: Authors, 2023)

Data base	Key words	Obtained results	Used articles
ScienceDirect Journals	*parametric AND Urban or CIM*	58	8
MDPI	*Parametric AND City Information Modeling OR Urban*	88	10
Cumincad	*"Parametric design" "City Information Modeling" "Urban plug-in" {summary} =~ m/urban/i*	94	19
	TOTAL	**240**	**37**

Of the 240 search results, 70 articles met the selection criteria with the theme of design, intervention and analysis at an urban scale, and were selected for a more detailed search. In order to identify whether these articles made use of parametric design tools, the keywords "parametric" "urban" and "tool" were searched in the abstracts, methodologies, results and discussions, which resulted in 37 articles meeting the research criteria. In each article, information regarding the research topic, modeling and visualization tools, parametric design plugins, additional plugins, and the databases used for model generation or analysis was documented. Subsequently, the topics were categorized into 11 groups based on the similarity of use cases and graphical maps generated in the studies. The databases were initially recorded based on their specific applications and subsequently categorized based on their frequency of use in the works. It was considered "Low" frequency when it had its use applied between 0% and 2.9% of the works, "Medium" when it was applied between 3.0% and 8.9% of the works, and "High" when it had its use applied between 9.0% and 14% of the works.

3. Results

The systematic review allowed to identify the intensity of use of each category of urban design/analysis involving parametric design as a complementary tool to urban design or CIM systems, where a classification was obtained according to the number of scientific articles that make use of one or more categories (Figure 1).

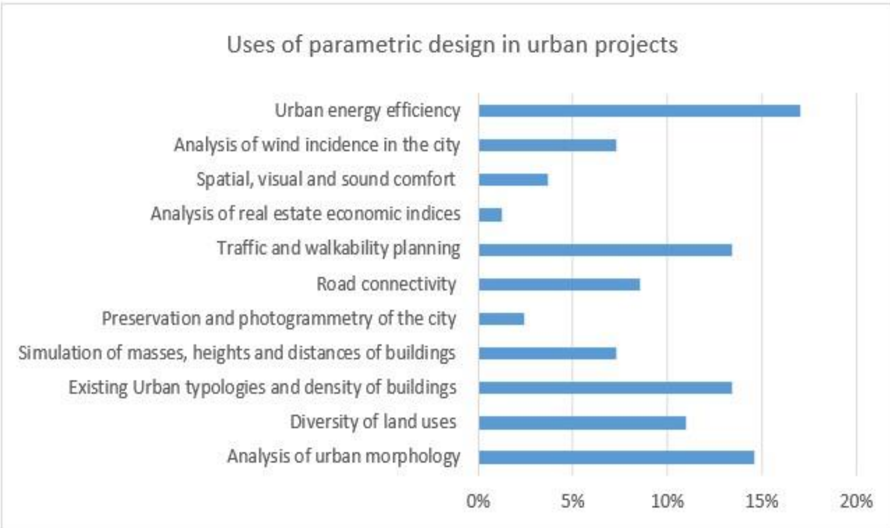

Figure 1. Uses of parametric design in urban projects. Source: Authors, 2023.

3.1. URBAN ENERGY EFFICIENCY

This was the category in which the largest number of works was registered, present in 17.1% of the works. The authors of the projects were able to generate climate analysis in public spaces, obtaining average temperatures in public roads, parks and around high-rise buildings, which also allows the identification of some patterns of urban typologies that generate certain climatic circumstances. There are also works involving the analysis of the energy consumption demand of urban clippings from data archetypes and "Digimap" data of existing buildings, which already predefine consumption values according to historical records. There is still, among the possibilities of uses, the identification of the influence of the solar reflection of urban paving on the average local temperature, the identification of the climatic effects of urban vegetation, studies for projects of structuring of photovoltaic plate network in a neighborhood, and sustainability analysis in CIM projects.

The authors mainly used the Grasshopper plug-ins such as "Ladybug" (Ladybug Tools, 2023), for sun path, radiation, microclimate and energy optimization. "Honeybee" plug-in (Ladybug Tools, 2023) is employed for simulation of buildings energy consumption and natural ventilation in order to simulate thermal conditions and generate graphs of energy demand and thermal comfort in public spaces. The "Dragonfly" plug-in (Ladybug Tools, 2023) is primarily employed for advanced daylighting and building performance analysis during the design phase, with a primary emphasis on optimizing daylighting and mitigating solar heat gain. The "Eddy3D" (Dogan; Kastner, 2018) plugin for Grasshopper serves as a valuable tool for strategically utilizing natural ventilation in urban settings. It enables the assessment of wind patterns around buildings and urban spaces, facilitating informed design decisions. Furthermore, this plugin proves instrumental in evaluating the environmental consequences of urban developments on the natural flow of wind.

Another plug-in for Grasshopper is "UMI" (Reinhart et al., 2013) which allows simulation of energy demand and daylighting, but in a limited neighborhood-scale selection. There is also the use of applications such as "Canyon Air Temperature (CAT)" with algorithmic-parametric functions for temperature analysis in urban streets, and "TRNSYS" (TRNSYS, 2023), engineering software with algorithmic-parametric functions for energy analysis and design optimization.

3.2. URBAN MORPHOLOGY ANALYSIS

Evident in 15.1% of the projects analyzed, this topic encompasses the design and analysis of typologies and geometries of neighborhood blocks or entire cities, with a complexity of algorithmic-parametric information to generate models from GIS data and maps usually made available by municipal management or government statistical data. The works analyzed involve mainly planning and simulation of urban form patterns, form syntax, morphological analysis of urban settlements, mapping and morphological classification of city zones, and parametric design concepts. The main Grasshopper add-on tools used by designers include "Dragonfly" (Ladybug Tools, 2023) for Grasshopper, which allows to generate geometries and urban meshes from databases, or to simulate through algorithms new possibilities. Another important tool is "Citymetrics Toolbox" (Lima, 2017), an algorithm for Grasshopper capable of enhancing urban configurations by measuring and optimizing their performance using metrics based on tangible principles. "Citymaker", which generates geometries, simulations and graphic maps related to urban morphology, topography, land use, buildings and urban roads. There are also options such as "CityEngine" (Esri R&D, 2008), used in ArcGis software, for procedural modeling of the city from GIS databases, and the "Dynamo" plug-in, for Revit software, with application more focused on project development and design of urban meshes in CIM, . The “CADMAPPER” is an important online tool that enables importing data to Revit to create urban geometries for further analysis in Dynamo (Figure 2).

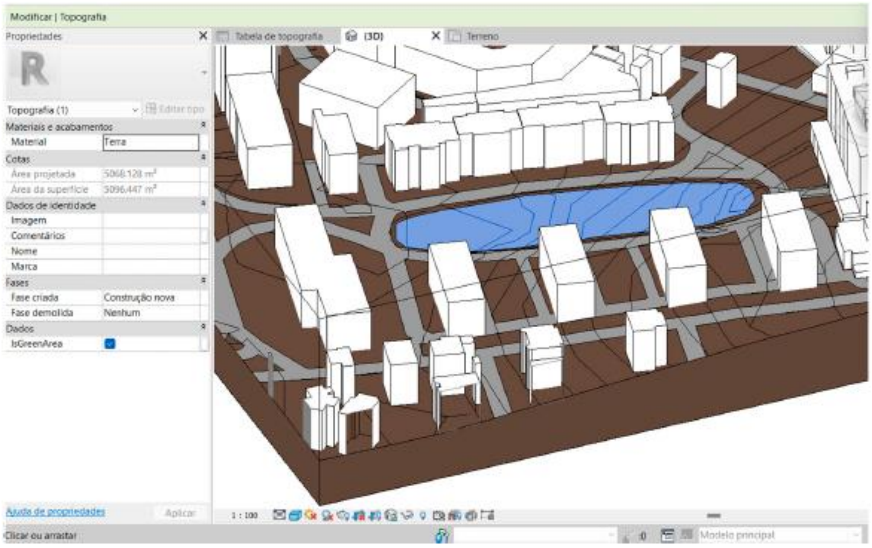

Figure 2. Urban data imported from CADMAPPER to Revit. Source: Authors, 2023.

3.3. TRAFFIC PLANNING AND WALKABILITY

This category was identified in 13.1% of the papers, involving the analysis of vehicle flow from algorithmic-parametric models based on government statistical data and collaborative databases such as "Open Street Maps", for forecasting future demands and planning road widenings. It is also possible to generate simulations of bicycle lanes, walkability networks on public sidewalks and walking paths in urban parks, to search for a greater number of alternative route solutions according to the flow demand in each section, to assist in the decision making of the most suitable road width path. Another significant functionality includes the generation of flow intensity hierarchy maps to anticipate congestion hotspots with high pedestrian and vehicular traffic in urban centers. This can assist in identifying the most crucial and strategic roadways to accommodate such high movement and, consequently, establish key commercial zones as part of urban planning guidelines managed by the city.

Several plugins, operating within Rhinoceros/Grasshopper, have the capacity to generate these functions, with one notable example being 'Citymetrics' (Lima, 2017). 'Citymetrics' can generate geometric solutions to identify optimal route alternatives for both pedestrians and vehicles. Additionally, it can leverage data obtained from sensors, traffic cameras, and even social networks for enhanced analysis and decision-making. The "Configurbanist" (Nourian et al., 2015) algorithm allows the identification of ideal points in the city for the implementation of bike lane networks and maps of zones of uses. The "Urbano Toolbox" (Dogan et al., 2018) allows to perform simulations of transport networks through urban indicators including simulation of travel time between points of the city. The "Shortest Walk" (Piacentino, 2011) allows to calculate the most optimized distance between two points of the city. The algorithm "Simic" (Souza, 2018) allows to generate simulations of urban traffic, public transport systems and vehicle and bicycle sharing systems.

There are also software options such as "MATSim" (MATSIm Community, 2023), which allows the creation of real-time traffic simulation models to assist in transportation planning, and the "Urban Network Analysis -UNA" plug-in (Sevtsuk, 2018), which operates in Rhinoceros through geospatial data from databases or by information surveys carried out by the designer on site. UNA allows analyzing the connectivity and accessibility of the urban network, generating data and estimates of flows of people and vehicles, being capable of assisting in infrastructure expansions and implementation of urban accessibility. For Soltani et al. (2019) the accessibility analysis in UNA showed different patterns when using different points of attraction, and also had the differential of allowing to focus on the layout of the building, while this was not possible in other software. A software allied to the development of urban flow solutions is CityEngine (Esri R&D, 2008), which in addition to allowing urban design solutions, is capable of generating pedestrian and vehicle traffic simulations in different scenarios, taking into account road width, intersections and traffic lights generated by databases.

3.4. EXISTING URBAN TYPOLOGIES AND BUILDING DENSITY

This modality was present in 13.1% of the papers. Many of the projects consist in the analysis of existing building typologies patterns, usually generated in collaborative databases such as "Open Street Maps", GIS databases or municipal databases. Grasshopper has been the most widely used software for this type of urban form analysis. It enables designers to define patterns such as “House clusters”, “Row houses”, “tall buildings”, “Long thin houses”, and any other desired categories. These groupings allow designers to analyze standards such as average built areas, building density by region, average number of floors, and many other urban patterns. "Urban Network Analysis" (Sevtsuk, 2018), is a useful tool for buildings density measurement, integrated with land use and spatial network. These urban studies allow urban designers to better understand the impacts of high density on urban centralities, typically related to visual and thermal comfort. Another functionality for urban management involves simulations of building heights and volumes in different or random parameters, through categorization by graphic maps with color legends, to simulate the scenario resulting from the applications of the city's urban indices and plan the optimal building indices for future land use.

3.5. DIVERSITY OF LAND USE

This category was found in 11.1% of the analyzed projects. It involves the mapping and parametric categorization of existing buildings, utilizing data from "Open Street Maps" databases or municipal databases, to generate 3D models. These models are represented with distinct colors and appropriate legends, which serve to identify and classify buildings according to their functions, including commercial, residential, educational, healthcare, urban parks, and other social purposes within the urban space.

The algorithm “Simic” (Souza, 2018) for Grasshopper calculates the ratio of reported targets within a specific service category to the total number of locations in the analyzed area. It can also calculate the ratio between the sum of residential and non-residential areas in an urban setting and compares these ratios. Similarly, “CityMetrics” (Figure 3) enables measuring the diversity of an area before and after an intervention.

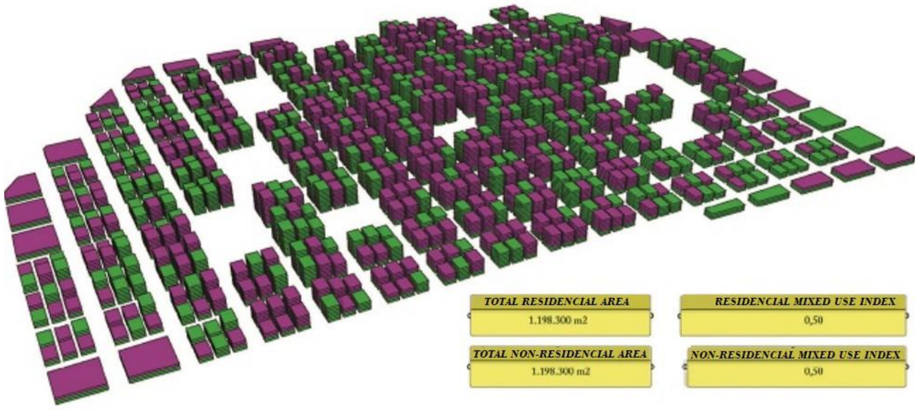

Figure 3. Building use indexes in CityMetrics. Source: Lima, 2017.

3.6. SIMULATION OF MASSES, HEIGHTS AND DISTANCES OF BUILDINGS

This category was found in 7.1% of the projects. Simulations are generally worked out for parameterized generation of buildings with random volumes and heights, to allow studies of analysis of fictitious cities or even for use in 3D renderings. Studies can also be carried out to calculate the relationship between mass and distance between existing buildings, for later comfort analysis. These analysis of typologies, masses and land uses can be performed through algorithmic-parametric modeling plug-ins for Rhinoceros/Grasshopper, such as "Citymaker" (Beirão, 2012), for creation of buildings geometries, "Citymetrics" (Lima, 2017), for the creation of parametric buildings and houses models with different functions for analysis. The "Elk" (Logan, 2023) Grasshopper plugin allows wide range of city scale modelling, but only inputs data out of “Open Street Maps” GIS databases.
CityEngine (Esri R&D, 2008), is an important CIM software which operates through ArcGis for parametric and procedural urban modeling, including buildings, street network. The OGOS+ (Chatzi; Wesseler, 2020) is a useful plugin for Grasshopper that allows mass studies of building clusters in Germany. It enables urban designer to find optimal built areas for German local zoning laws.

Another efficient tool is Wallacei X, a multi-objective generative solver for Grasshopper which employs evolutionary algorithms to conduct simulations. These generative simulations encompass a wide range of tasks, including testing spatial arrangements, identifying areas with higher density and connectivity, and optimizing sun exposure when used in conjunction with Ladybug Tools.

3.7. ROAD CONNECTIVITY

This analytical category was identified in 9.1% of urban studies and centers on the analysis of routes, as well as the classification of the significance of urban roads concerning urban centers. This analysis yields maps that illustrate streets through connectivity 'nodes' and flowcharts. It showcases the potential for multiple pathways to a common destination, each influenced by varying degrees of complexity. Additionally, it highlights the consequences that arise in spaces where there is a higher flow of traffic. Connectivity studies usually present the degree of difficulty of travel, not only based on distance, but also on the number of topological steps and detours required to reach the destination, which allows classifying certain neighborhoods as easy or difficult to access. An example is the "DecodingSpaces Toolbox" (Figure 4) application for Grasshopper, which allows you to create points of interest from "nodes", and thus generate possible connectivity between neighborhoods and centralities, along with flow maps.

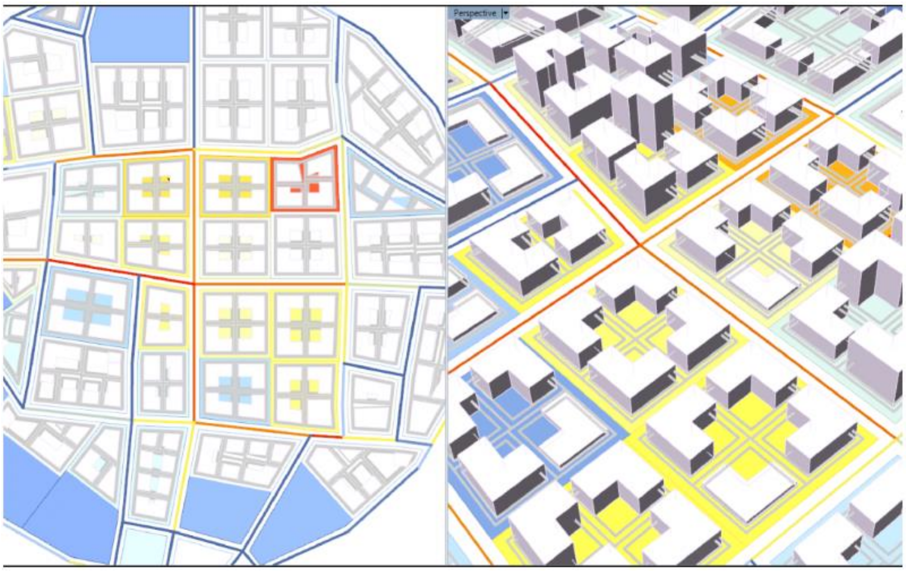

Figure 4. Decoding Spaces Toolbox. Source: Koenig et al., 2018.

3.8. WIND INCIDENCE ANALYSIS IN THE CITY

This category was identified in 7.1% of the works, involving the analysis of winds in urban spaces and their relationship with clusters of high-rise buildings, aiming to provide comfort to people, mainly with the Grasshopper plug-ins "InFraRed" (Duering et al., 2020) and "Swift" (ODS Engineering, 2017), important plug-ins for Grasshopper for complex urban wind analysis which also involves simulations and interconnections between elements based on "nodes".

3.9. SPATIAL, VISUAL AND SOUND COMFORT

This was another category identified in 4.1% of the research, involving the visual quality of spaces, such as fields of visibility of the skies and green areas, and the noise caused by vehicles and urban noise. aerial drones in public spaces. The “UAM Noise Generator” is an example of algorithm for Grasshopper which was developed to simulate external noise from moving devices such as drones and vehicles. The "Eddy3D" plugin is a Grasshopper tool designed to enhance the comfort of public spaces. It achieves this by measuring space dimensions and analyzing wind patterns, ultimately generating comfort indices for public areas. The "Ladybug" (Ladybug Tools, 2023) is a Grasshopper plugin capable of generating sky view analysis in urban spaces, considering obstacles such as buildings. It generates a visibility factor at different points, depending on the influence of the surroundings of the 3D urban model. Grasshopper itself offers a complete toolkit for urban planners, enabling the creation of isovist analyses at an urban scale.

3.10. PRESERVATION AND PHOTOGRAMMETRY OF THE CITY

This modality was found in 2,1% of articles searched, with analysis of the historical preservation of urban spaces involving photogrammetric surveys of the city and buildings for modeling public spaces based on point cloud technologies with "lIdar" technology, which establish fidelity of geometries and textures. Revit can be used to generate comprehensive models of historical buildings with a high level of detail to prevent the loss of information caused by natural disasters, for example. Dynamo is capable of assisting in this process by assigning codifications to 3D models to establish connections between building data sets during the conversion to the 3D model, thus preserving related information.

3.11. ANALYSIS OF REAL ESTATE ECONOMIC INDICES"

This is the topic that generated fewer results, appearing in only 1.1% of articles. It involves the correlation of land use with economic indicators related to construction and public maintenance expenses. Grasshopper is employed to simulate spatial configurations, enabling a deeper understanding of how environmental variables, such as spatial distribution, buildings heights and climate, could impact building costs and comfort.

4. Discussions

Among the tools identified and listed, there are algorithmic-parametric design applications and plug-ins capable of assisting in different types of urban projects. These tools can also be subdivided into three major common fields, which broadly involve Urban Modeling, Flow Analysis and Comfort and Performance (Figure 5).

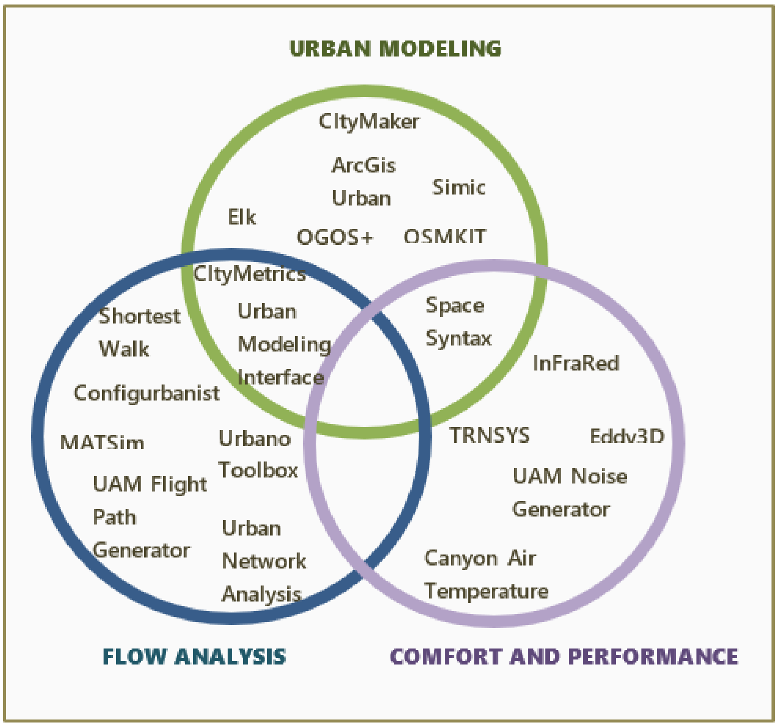

Figure 5. Uses of Parametric Design Tools. Source: Authors, 2023.

Some recent tools have been found. These tools include ArcGis Urban (Esri R&D, 2019) for scenario planning and impact assessment. ArcGis Urban allows users to create 3D models of buildings, infrastructure, land use and development zones, involving simulations taking into account factors such as population density, land use and public transport to evaluate different planning strategies. This makes it possible to carry out traffic assessments, sustainability analysis and accessibility analysis to ensure that development plans are efficient.; Osmkit (Cheng; Hou, 2019), which is an open-source tool designed to simplify working with OpenStreetMap (OSM) data. This tool allows you to import, export, manipulate and analyze OSM geospatial information. Its functionalities include data import/export, map element manipulation, spatial analysis, data visualization and task automation. Osmkit is highly customizable and useful for developers, GIS analysts and urban planners who want to use OSM geospatial data in an efficient way.

Other recently developed tools are UAM Flight Path Generator and UAM Noise Generator (Ortner; Huang, 2020), both for Rhinoceros and Grasshopper. The UAM Flight Path Generator, as shown in Figure 6, has been developed for urban air mobility planning, envisioning a future where drones and air taxis become prevalent modes of delivery and transportation. In anticipation of this transformation, the planning of these aerial flows gain importance, and to achieve this, urban spaces must be conceptualized as three-dimensional landscapes. The algorithm makes it possible to trace routes within flow corridors, and enables the testing of the most efficient aerial routes throughout the city, ultimately optimizing drone range and performance.

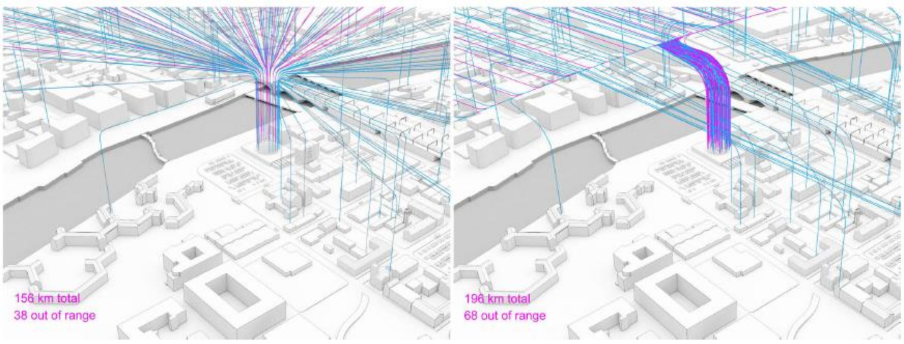

Figure 6. UAM Flight Path Generator. Source: Ortner; Huang, 2020.

Considering the noise that these aerial devices can cause, the UAM Noise Generator was developed with the noise impact on inhabitants in mind. This algorithm uses a model of noise propagation in outdoor environments, with calculations of sound pressure levels over varying distances with moving devices.

InFraRed (Duering et al., 2020) is a machine learning wind-prediction for urban-scale wind simulation, and operates in Rhinoceros and Grasshopper (Figure 7). It is a very useful tool for estimating wind flow at ground level in urban areas measuring 250 x 250m. It has some limitations, as it is unable to take into account the topographic levels of the terrain, and requires a computer with good performance and can take a long time to process data.

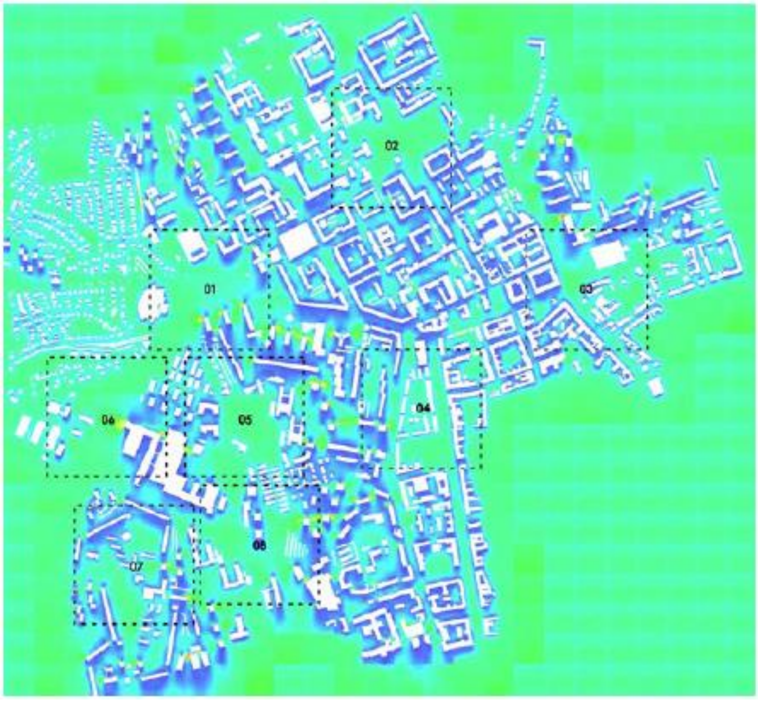

Figure 7. Wind speed prediction with InfraRed plugin. Source: Kabošová et al., 2021.

OGOS+ (2020) is also a recent tool available for building mass studies and potential construction area analysis, but it is limited to Germany. As can be seen below in Table 2, the applications analyzed are mostly developed for the Rhinoceros/Grasshopper parametric modeling and design platforms, which due to their capabilities for processing geometries with large amounts of data, and for providing complete tools for data analysis functions, can be seen among the most suitable for this type of design study and analysis.

TABLE 2. Algorithmic-parametric tools for urban design and analysis (Source: Authors, 2023)

Plug-in/app	Year	Operation	Applications	Compatible Software
ArcGis Urban	2019	App	Scenario planning, impact assessment	
ArcGis CityEngine	2008	App	Urban modeling	
Canyon Air Temperature (CAT)	2006	App	Temperature on urban roads	
CItyMaker	2012	Plug-in	Urban modeling, grammar of form	Rhinoceros/ Grasshopper
CityMetrics	2017	Plug-in	Walkability, diversity and density	Rhinoceros/ Grasshopper
Configurbanist	2015	Plug-in	Walking, cycling	Rhinoceros/ Grasshopper
DecodingSpaces Toolbox	2017	Plug-in	Network of roads, allotments and buildings	Rhinoceros/ Grasshopper
Eddy3D	2018	Plug-in	Climate simulation, air circulation	Rhinoceros/ Grasshopper
Each	2012	Plug-in	Maps and topographies	Rhinoceros/ Grasshopper
Gismo	2012	Plug-in	Spatial, solar, isovist, morphology analysis	Rhinoceros/ Grasshopper
InFraRed	2020	Plug-in	Wind simulation	Rhinoceros/ Grasshopper
MATSim.	2013	Plug-in	Traffic simulation	Rhinoceros/ Grasshopper
AUGUST+	2020	Plug-in	Study of masses of buildings	Rhinoceros/ Grasshopper
OSMKIT	2019	Plug-in	Urban modeling	Rhinoceros/ Grasshopper
Shortest Walk	2011	Plug-in	Walkability	Rhinoceros/ Grasshopper
Simic	2018	Plug-in	City Information Modeling	Qgis/ Rhinoceros/ Grasshopper
Swift	2017	Plug-in	Wind simulation	Rhinoceros/ Grasshopper
TRNSYS	1976	App	Wind simulation	
UAM Flight Path Generator	2020	Plug-in	Urban air mobility	Rhinoceros/ Grasshopper
UAM Noise Generator	2020	Plug-in	Sound comfort	Rhinoceros/ Grasshopper
Urban Modeling Interface (UMI)	2013	Plug-in	Urban modeling, walkability, Environmental analysis	Rhinoceros/ Grasshopper

Urban Network Analysis (UNA)	2012	Plug-in	Connectivity, accessibility and flows of vehicles and people	ArcGIS/ Rhinoceros
Urbano Toolbox	2018	Plug-in	Walkability, accessibility, road networks	Rhinoceros/ Grasshopper

An important pillar of urban parametric design that has been highlighted is the projection and analysis of motor vehicle flows, the operability of cycle lanes and walkability on public roads, which are usually surveyed from access to databases generated by public surveys that evaluate the user experience and make official records of vehicle flows. This information allows the identification of the real needs for the implementation of new roads, cycle lanes or the forecast of a road widening after simulations that indicate trends of increased flow in certain regions of the city. It is also possible to highlight as a strong point of parametric design the execution of energy efficiency analysis, which according to the research data, can cover solar incidence, energy demand of buildings, use of thermal energies and average temperatures in certain regions of the city, and there are also professionals who evaluate the influence of winds on buildings with detailed reports on the impact of these simulations. To create these virtual scenarios, different types of databases can be used, depending on the type of analysis or simulation to be performed (Table 3).

These databases are used by several plug-ins, such as Grasshopper, together with ghPython textual programming elements, Elk (Logan, 2023) for map generation, and Lunchbox, for coding and data collection. They are used to create models and simulations of energy, natural light, wind, drone flow, among others, which can generate simulations of alternative scenarios from statistical data to evaluate changes in urban interventions and assist in sustainable urban planning.

Lima, Costa and Rosa (2020) emphasize that such applications should not be seen as substitutes for human activity in the process of project development and analysis, but rather as available tools that can be used to improve analysis and planning skills in urban contexts, and contribute to the understanding and solution of contemporary urban challenges, such as urban mobility and land use planning.

TABLE 3. Main databases used in urban projects (Source: Authors, 2023)

Data Types	**Functionality**	**Frequency of use**
CADMAPPER	Map files database	Low
CCI-Reanalyzer	Data with information about the Earth's climate	Low
CGA scripting language	Programming language for creating 3D building models	Low
CityGML	XML data for 3D modeling of city geometry/topology	Low
Aerophotogrammetric data	Data collected through photographs	Average
CFD Data	Computational Fluid Dynamics	Average
Climate data	Records collected about weather conditions	Average
Building archetype data	Database created based on local energy codes	Low
MRT Contact info	Mass transit system data	Low
Official government data	Databases provided by government institutions	Average
Raster data	Spatial data to represent continuous surface information	Low
TMY Contact info	Summary meteorological dataset	Low
Digimap	Digital maps and geospatial data service	Low
EnergyPlus weather	Weather dataset used by EnergyPlus	Low
ENERGYui	Generates building energy efficiency labels in "EnergyPlus"	Low
GIS *databases*	Geographic databases	High
Public vehicle information	Statistical data collected from transportation and vehicles	Low
Satellite maps	Mapping data from satellites	Low
MathNet.Numerics	Numerical library that provides mathematical functions	Low
Point cloud per tec. Deal	Three-dimensional data collection with laser technology	Low
Open Street maps	Geospatial Data Platform	High
Open Topography	Topographic data platform	Low
Local searches	Data collection by the author of the project	Average
PostgreSQL	Relational Database Management System (RDBMS)	Low

5. Conclusion

Through the analysis, it is possible to understand that the demand for digital technologies such as parametric design applied in urban projects is gaining ground and establishment, especially with regard to energy performance analysis, urban flow analysis, and urban structure modeling systems in large city areas. These tools provide accurate results, with a flexibility of analysis through external databases that would have its execution limited if executed only through the CIM method, which shows the relevance of adopting parametric design as a complementary system for urban projects.

The management of the model may have a management problem due to the scarcity of professionals with mastery of parametric design tools, in addition to requiring higher performance computers. Despite the challenges, the solutions performed by algorithmic-parametric simulations can generate a large number of possibilities, embracing a set of solutions that suit the specific conditions of each morphological problem. Considering the importance of these tools for urban management, their adoption should be encouraged and discussed by public managers and urban planners, since the data presented show the importance that parametric design tools are gaining in the elaboration of projects, interventions and urban requalification.

Acknowledgements

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2.B.

PERFORMATIVE-DRIVEN DESIGN AND DIGITAL GREEN - I

ENHANCING HYGROMORPHIC PROGRAMMABLE PROPERTIES USING NATURAL LOCAL MATERIALS

The Case of Albizia Lebbeck Trees

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Abstract. This paper explores the use of Albizia Lebbeck wood as a hygromorphic programmable material in adaptive architectural building skins. Several studies have investigated the use of hygromorphic behavior in developing adaptive architectural façades. Very few however have attempted to explore and evaluate the use of natural local materials in their specific climatic and cultural context, especially in the Arab World. Multiple experiments and simulations were conducted on Albizia Lebbeck wood samples as a material widely abundant in Egypt. The results demonstrate high potential for bending deformation, for use as a programmable adaptive façade panel. Compared against typical kinetic and static façade prototypes in an office space case study in Alexandria, Egypt, this double skin programmable material was shown to potentially improve performance in interior spaces in terms of light penetration and distribution without causing high levels of illumination or glare, while demonstrating low-cost and eco-friendly benefits for implementation as responsive façade prototypes.

Keywords: *Hygroscopy, Hygromorphic design, Adaptive Architecture, Responsive façades.*

ملخص. يستكشف هذا البحث استخدام خشب اللبخ كمادة قابلة للبرمجة في واجهات المباني المعمارية التكيفية. وقد بحثت العديد من الدراسات في استخدام السلوك الرطب في تطوير الواجهات المعمارية التكيفية. ومع ذلك، لم تبحث سوى عدد قليل جدًا من الدراسات فى مسألة استكشاف وتقييم استخدام المواد المحلية الطبيعية في سياقها المناخي والثقافي المحدد، وخاصة في العالم العربي. تم إجراء العديد من التجارب والمحاكاة على عينات خشب اللبخ باعتبارها مادة متوفرة بكثرة في مصر. أظهرت النتائج إمكانية عالية لتشوه الانحناء، لاستخدامها كألواح واجهات مبانى قابلة للبرمجة. بالمقارنة مع النماذج الأولية للواجهات الحركية والثابتة في دراسة حالة للمساحات المكتبية في الإسكندرية بمصر، تبين أن هذه المادة المزدوجة القابلة للبرمجة تعمل على تحسين الأداء في المساحات الداخلية من حيث اختراق الضوء وتوزيعه دون التسبب في مستويات عالية من الإضاءة أو الوهج، بينما تظهر فوائد منخفضة التكلفة وصديقة للبيئة للتنفيذ كنماذج أولية سريعة الاستجابة للواجهة.

الكلمات المفتاحية: *الخاصية الاسترطابية، تصميم باستخدام الخواص الاسترطابية، العمارة التكيفية، واجهات سريعة الاستجابة.*

1. Introduction

Global warming is currently a priority concern, given its strong negative impact on human activity and the future of the planet, especially with construction activities that involve using non eco-friendly resources and materials. Reducing these harmful impacts is crucial to sustainable design approaches (Suhamad & Martana, 2020). The use of abundant local materials and resources is key to this approach. However, the availability of these materials may vary from one location to another. Geographical location, climatic zone, and the physical and chemical characteristics of materials could all potentially impact their availability (Adekunle & Odeyale, 2008).

The ecological inefficiency of modern design approaches drove the need for an evolution in architectural design approaches. The development of intelligent and sustainable architectural methods constitutes a promising direction to address ecological enhancement in contemporary architecture. New materiality opportunities become available through technological innovations at various levels of the architectural design process. To create more sustainable architecture, recent approaches such as material-based design investigate how material behavior and qualities could be considered from the onset of the design process (Asefi & Afzali, 2016).

Computation has typically contributed to innovative techniques and strategies related to programmable materials and adaptivity (Ritter, 2007). One of these strategies involves capitalizing on hygroscopic behavior of materials, a process that was initially inspired by the shrinking and swelling and morphological deformation of pinecones in their response to variation in humidity levels (Marysse, 2016).

Several studies have investigated the use of this hygromorphic behavior in developing adaptive architectural façades with zero-energy consumption by replacing high-cost mechanical actuators with low-cost low-tech natural materials (El-Dabaa and Abdelmohsen, 2023). These studies have typically involved the investigation of manufacturing methods of hygromorphic adaptive façades, response motion behavior evaluation and tracking, analysis of the current applications of hygromorphic design in real weather conditions, and performance prediction.

Only a limited number of studies have attempted to explore and evaluate the use of natural local materials in their specific climatic and cultural context, especially in the Arab World. As a material for construction, wood is a natural flexible material that can respond to humidity. Its production is characterized by its minimal energy consumption and waste production compared to steel and concrete (Julian & Fukuda, 2021; Julian et al., 2019). Wood extracted from local trees in southern Egypt, such as Albizia lebbeck trees, exhibit such potential. Albizia lebbeck trees are fast-growing trees whose wood features numerous possibilities as an alternate building material for sustainable construction purposes (Hassan, 2020; Julian et al., 2022).

This paper investigates the use of hygromorphic local materials extracted from Albizia lebbeck trees. The paper first analyses the Albizia lebbeck wood based on its hygroscopic ability to absorb and retain moisture, and dissects its cell structure which is primarily based on condensed grains. The extracted wood layers exhibit unique characteristics, as they can completely deform and return to their initial state, providing the material with unique durability features.

Several experiments and tests are then conducted on these local wood materials in a controlled environment under different humidity and temperature conditions. The response of these materials, in terms of motion, deformation behavior, and speed, is then calculated and measured using image analysis and numerical modeling methods. The experiment output in terms of morphological capabilities and responsive parameters are also documented in material data matrices. By comparing the results of these experiments to a base case; in this case a kinetic unit based on mechanical actuators, the discrepancies in terms of response, energy consumption, and cost are determined.

Based on the experiment results, a computational interface using Grasshopper is used to simulate and forecast the material responses in the context of a large-scale façade design in a specific setting in Cairo, Egypt, based on the resultant parameters. Environmental optimization is conducted to evaluate the outcome and achieve thermal comfort within a given interior case study space.

2. Albizia Lebbeck Wood Properties

As a construction material, wood is a natural material that has supplementary benefits such as flexibility in terms of response to humidity and immunity to corrosion from high humidity in tropical areas (Julian & Fukuda, 2021; Julian et al., 2019). According to reports, wood production minimizes energy consumption and produces less air, water, and gas pollution than steel and concrete. Many local materials have that potential, including Albasia lebbeck – a fast-growing tree planted especially in the southern areas of Egypt – whose extracted wood has many possibilities for construction usage (Hassan, 2020).

In recent years, the southern governorates of Egypt have seen a significant increase in growing Albizia lebbeck, a Fabaceae family of deciduous trees that are spread across Egypt. These trees are grown for shading and decorative purposes in Egypt because of the unusual shape of their blossoms. Additionally, they have numerous industrial applications such as paneling and shipbuilding (Hassan, 2020). They are also characterized by their fast growth and can be used as a building material for enhancing sustainable development methodology due to their extensive use in plantations and being one of the essential alternatives to wood sources for making environmental sustainability more feasible (Julian et al., 2022)

Albizia lebbeck wood is highly valuable because of its resistance to white ants and fungi that cause wood to rot. As shown in Figure 1, these wood chemicals consist of crystalline areas and lignin as a polymer that resists the material from the microorganisms' attack in the cellulosic bonds, as well as extractives that resist biological agents as a natural resistance role, such as fungi and beetles. Those characteristics control wood mechanical properties, affecting the end-uses of wood products such as thin paper industries (Hassan, 2020).

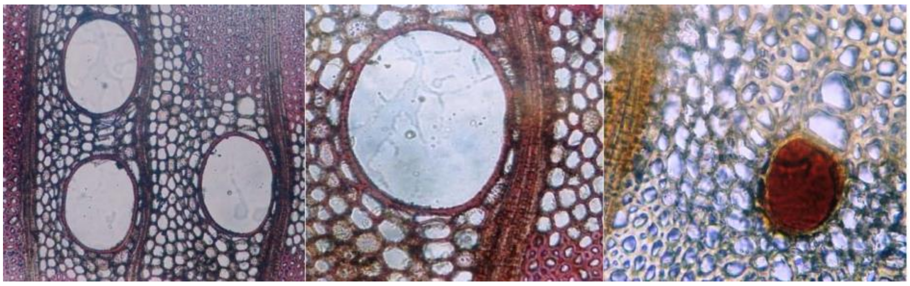


Figure 1. Transverse section of stem heartwood of Albizia Lebbeck, *Left*: Large vessels surrounded by wood parenchyma, wood fibers and three biseriate medullary rays, *Middle*: Wood parenchyma and biseriate medullary rays, *Right*: Medullary rays and vessel filled with reddish brown content (Yadav et al., 2011).

Albizia species were tested to evaluate their anatomical wood features (Figure 2) to assess the suitability of the extracted wood for production. The selected sample was tested using standard methods, and the wood species was diffusely porous. Quantitative wood anatomies characteristics such as pore diameter, fiber length, ray width, and vessel length and width were crucial for taxonomic classification in this genus (Odiye et al., 2019). Albizia wood porous vessels are mainly solitary with radial pore and clusters, fibre libriform, non-storied, non-septate with large lumen and narrow walls (Odiye et al., 2019).

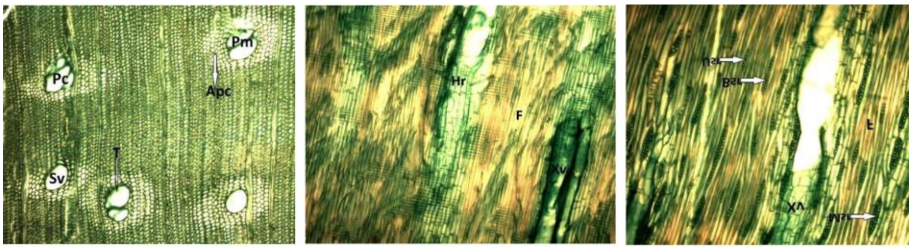


Figure 2. Photomicrographs of the wood anatomical features of Albizia Lebbeck with transverse sections, tangential sections and radial longitudinal sections (Odiye et al., 2019).

To solve more issues related to sustainability in architecture, assessing the environmental effects of material choices is becoming more crucial. Since wood material includes 50% carbon during its growth, absorbing carbon dioxide from the air using wood as a building resource is one of the most efficient ways to reduce carbon dioxide emissions from buildings from a sustainability perspective. In short, using wood products helps store more carbon, reducing the consequences of global warming (Julian et al., 2022).

Using wood in the construction industry is one of the favored strategies to reduce carbon dioxide emissions. Wood buildings require significantly less energy during construction than other materials, such as bricks, aluminum, steel, and concrete. Albizia lebbeck, in addition to being cheap and easily acquired due to its fast-growing features, also has extensive pliable features in engineering and construction (Julian et al., 2019).

Due to the difference from one tree characteristics to another, wood textures differ from one cut sheet to another (Figure 3), although the same tree of Albizia Lebbeck can produce different textures and colors. The material fibres and grains density affect the moisture absorption amount. Upon conducting multiple experiments on samples with different thicknesses and shapes, it was observed that Albizia Lebbeck bright sheets react directly to moisture with the ability of temperature resistance, which increases the durability of material capability.

Figure 3. Local wood material samples utilized for the experiments, Left to Right: Albizia lebbeck Heartwood, Cinnamomum camphora, Melia azedarach, Albizia lebbeck sapwood.

3. Experiment

3.1. MATERIAL SELECTION AND FABRICATION PROCESS

Four local wood materials extracted from Egyptian trees were tested through the fabrication and experimental process shown in Figure 4. The process starts by extracting wood bulks from the tree log and dividing them into multiple sheets with different thicknesses. The sheets are then fabricated with different shapes to be tested under high humidity conditions.

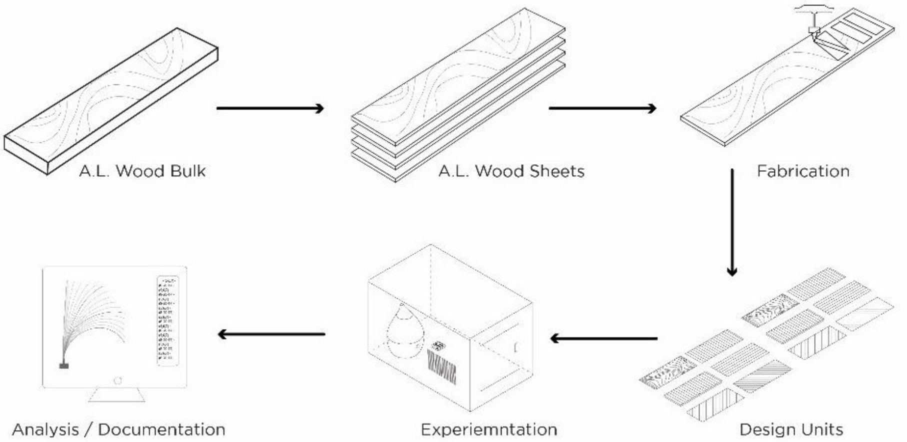


Figure 4. Fabrication and experimental process for Albizia Lebbeck wood sheets.

The first attempts of testing the wood sample experiments demonstrate the material’s responsive capability to moisture. The test was applied for a rectangle sample of Albizia Lebbeck wood with dimensions of 185mm length, 60mm width and 1mm thickness. The material shows the ability of moisture absorption, and its reaction capabilities causes bending motion, as shown in Figure 5.

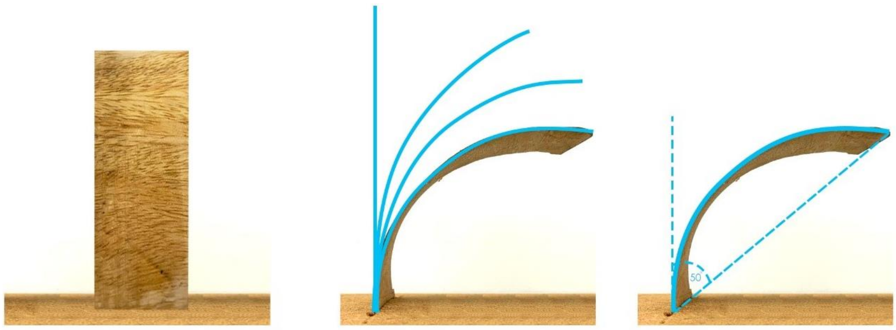


Figure 5. First attempt of experiment showing Albizia lebbeck material reaction capability.

Interactive architecture is well known approach to design dynamic spaces and objects that can accomplish a variety of human activities. The creative merging of embedded computation with tangible kinetics provides these complex physical interactions. Physical movement in architecture can be categorized into five types; rigid, soft-flexible, elastic, pneumatic, and deformable, which this study is concerned with. Deformable elements are mostly utilized in small-scale movements and large surface flexible transformation. Based on the material composite and properties, deformation occurs in soft-flexible and elastic bodies and rarely in plastic materials that need forces to deform irreversibly. Different types of motion and deformations typically exist in the literature, the most important of which are bending, shear, and rolling (Elkhayat, 2014).

3.2. PROGRAMMABLE DESIGN PROTOTYPE

The programmable dimension in the suggested prototype in this paper is based on the biomimicry process of the lizard skin (Trapelus Pallidus) and mimicking the harvesting techniques of its microstructural skin through its capillaries, which works as absorption elements, conveying the moisture from one region to another through these tunnels. The design proposal emphasizes and reflects these strategies to facilitate moisture harvesting and transmission through the whole façade. Also, the diamond and hexagonal diamond division patterns reflect the self-shading of the skin inspired by the lizard's outer skin geometry. Using this inspiration, we build on the impact of the moisture and deformation behavior of Albizia Lebbeck wooden samples as a prototype composed of triangular panels (50cm x 50cm unit with 0.5cm sample) as part of a large-scale adaptive façade and its responsive behavior through time upon applying moisture, as shown in Figure 6.

Figure 6. Morphological transformation of the material unit prototype.

The experiment initial results show an immediate and strong material morphological transformation of the wooden panel upon acquiring and retaining moisture based on the wooden fiber composition, thus facilitating the penetration of humidity between its fibers. Also, the deformation patterns of the prototype demonstrate a bending transformation, which acts as a dynamic responsive louvre that allows for light penetration and transmission, thus demonstrating its potential in impacting spatial illumination and regulation of daylight penetration, as shown in Figure 7.

Figure 7. Patterns of deformation, light penetration, and shading effect of louver prototype.

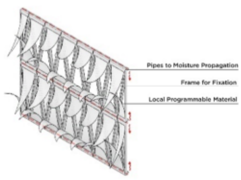
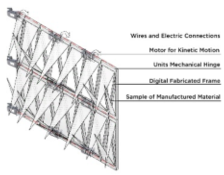
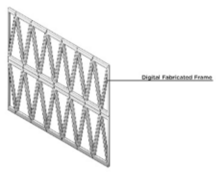
4. Results

As an observation, the experiments show that the Albizia Lebbeck wood samples react gradually upon applying moisture, resulting in responsive motion through bending transformation strategies, which emphasizes the material morphological capabilities based on humidity. Also, the sample transformation can act as louvres to avoid direct sun radiation with the ability to transmit light into interior spaces to reach maximum human comfort.

The results also emphasize the importance of utilizing local natural materials for sustainable design. This composite responds to external stimuli to adapt to different environmental factors under different conditions, in addition to utilizing local natural materials, which strongly influences the scope of material availability due to the location, flexibility of use, and low-cost affordability. By adopting the classification matrix (after Basarir & Altun, 2017) for façade design strategy, we observe how the specific mechanism of the Albizia Lebbeck programmable composite compares to other static and kinetic façade prototypes. This classification concerns comparing adaptation systems, motion mechanism details, and the relation between these techniques and multiple environmental factors, and the impact of these strategies on human comfort in architectural spaces.

This comparison emphasizes demonstrating the characteristics of each strategy regarding the scale, type of motion, and type of motion, which shows motion strategy requirements and its level of adaptation influence. These factors directly affect each mechanism's cost and environmental impact in terms of fulfilling the requirements of sustainable design principles. Accordingly, Table 1 compares between the Albizia Lebbeck programmable skin prototype, and a typical kinetic and static skin using the same dimensions, demonstrating the difference across the façade performance and environmental adaptation. This comparison is based on Basarir & Altun's (2017) classification matrix, clarifying the classification of each façade design strategy.

TABLE 1. Comparison between three building skin prototypes (programmable skin based on local wood material, kinetic skin, and static skin), based on Basarir & Altun (2017).

Comparison	Programmable Skin	Kinetic Skin	Static Skin
Unit Details			
Mechanism	Natural	Mechanical	Static
Actuator	Material Based	Motor-Based	none
Type of Motion	Bending	Varies	none
Type of control	Heuristic responsive indirect control	Responsive in-direct control	none
Degree of adaptability	Gradual	Hybrid	none
Type of movement	Bending	Rotation	none
Cost	Local wood material, fabrication, and moisture source.	Sensor and mechanical components, motors, connections, programming systems, fabrication, and maintenance.	Glazing and static skin fixation

5. Environmental Analysis and Simulations

An environmental simulation comparison was conducted for three façade designs. The proposed case study is a room as part of an office building located in Alexandria, Egypt. The room primarily used as an office space with dimensions (3m x 5m x 3m). The tested façade is for a South façade with opening dimensions of (2.4m height, 2.7m width, and 0.5m sill height), as shown in Figure 8. The three proposed designs are: (1) Albizia Lebbeck programmable skin, (2) kinetic skin, and (3) static skin.

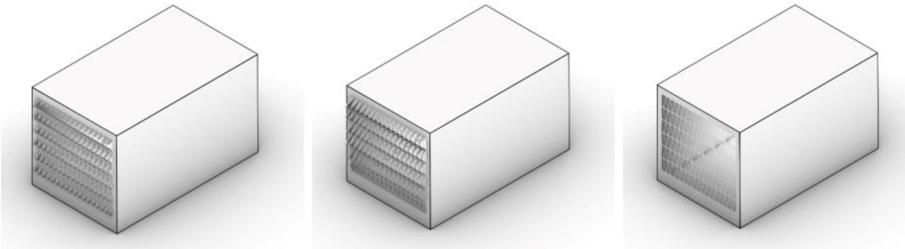


Figure 8. Three façade designs (programmable, kinetic, and static skins).

Based on the environmental analysis of Alexandria and the global horizontal illumination chart represented in lux units, the amount and time slots of acquired illumination is shown in Figure 9. Summer mornings are the peak impacted periods that causes high level of glare.

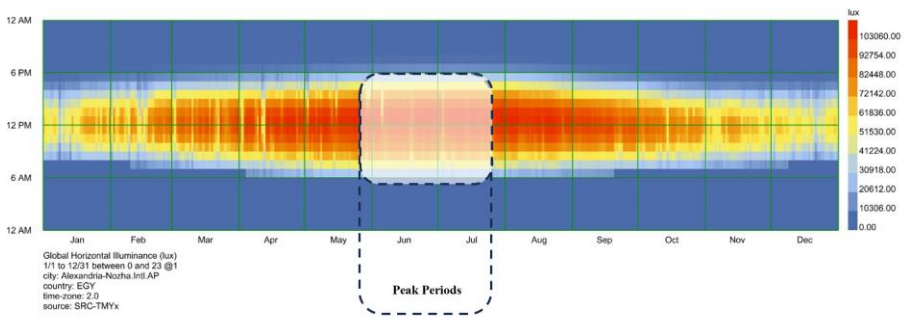


Figure 9. Chart illustrating the peak illumination periods for Alexandria, Egypt.

The sun path diagram for the same area also shows the direction and the specific time period of the maximum sun radiation and illumination, as shown in Figure 10. The building's environmental lighting performance is an important aspect of the building industry focus on green performance. Numerous studies have shown that combining the advantages of sunlight for human health with the common standards of comfort and visual acuity can result in a more healthy and effective work environment (Liu et al., 2022).

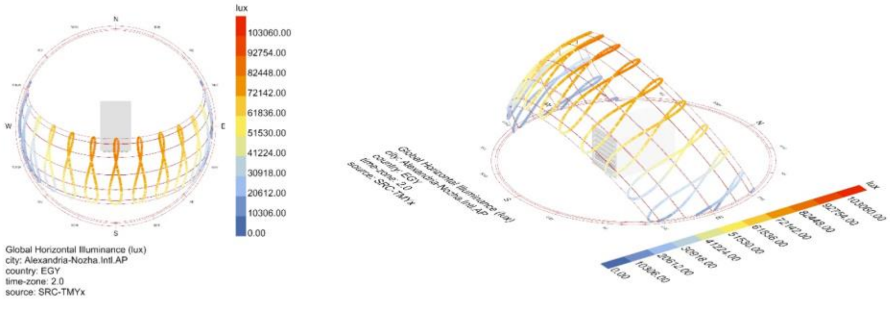


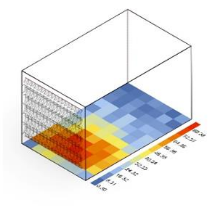
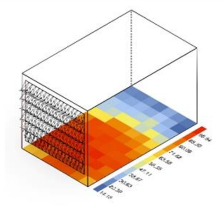
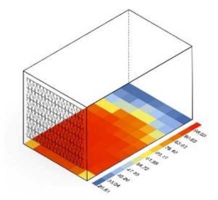
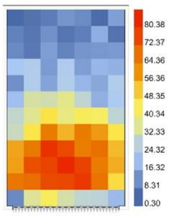
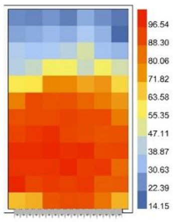
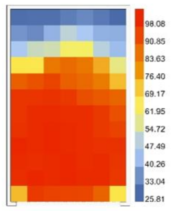
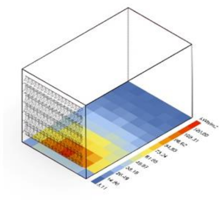
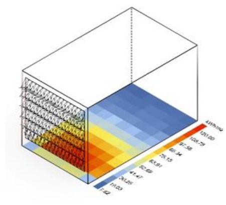
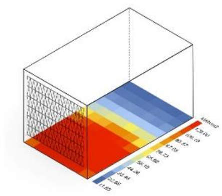
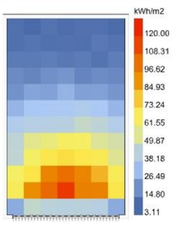
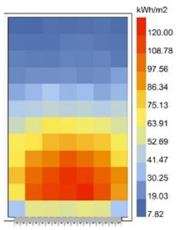
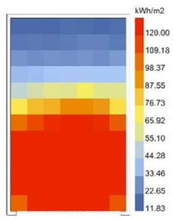
Figure 10. Sun path diagram showing radiation and illumination for Alexandria, Egypt.

Recent years have seen an increase in the use of parametric design tools and techniques as well as green building efficiency simulation techniques due to the advancement of computer-aided technology. A building's performance can be accurately optimized based on digital technology, which offers additional options. Building skin designs have been improved using parametric optimization platforms with the use of advanced technology in order to address multivariable, multi-objective problems; as a result, they currently represent the best option for enhancing productivity and decision-making accuracy (Liu et al., 2022).

Several Grasshopper plugins or apps are designed explicitly for simulating building performance. To carry out various simulation and optimization tasks, geometry built in Rhino or modelled in Grasshopper can be referred into Grasshopper. Most of these additional apps use verified third-party simulation engines, such as EnergyPlus or Radiance. A verified simulation engine, such as EnergyPlus, Radiance, or OpenFOAM, can transmit data in both directions with Ladybug and Honeybee. They can also be integrated into other simulation platforms, such as Openstudio. Various thermal and visual simulation options available to the user can satisfy most performance simulation objectives (Bazafkan, 2017).

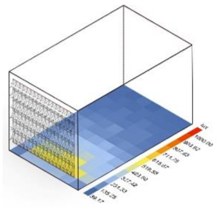
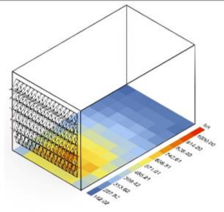
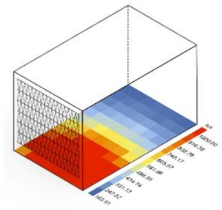
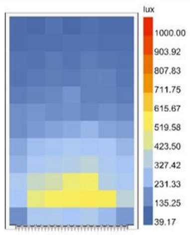
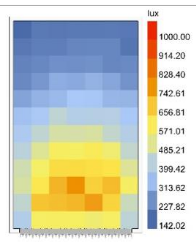
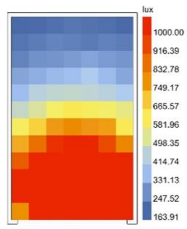
A daylight and radiation simulation was conducted for the annual analysis of the spaces exposed to daylight and radiation during the year for the three façade prototypes. The daylight autonomy results are in percent (DA). The study emphasizes the percentage of the period that is exposed at each sensor of the interior grid. At the same time, the cumulative radiation values reflect the radiation and irradiance over the year into account for the ambient reflections of the radiance.

TABLE 2. Annual daylight and radiation values for programmable, kinetic, and static façades, using Ladybug and Honeybee plugins.

View	Programmable	Kinetic	Static
Isometric View of **Annual Daylight** (Using Ladybug and Honeybee)			
Plan View of **Annual Daylight** (Using Ladybug and Honeybee)			
Isometric View of **Annual Radiation** (Using Ladybug and Honeybee)			
Plan View of **Annual Radiation** (Using Ladybug and Honeybee)			

Based on the previous analysis of the illumination peak period, the next step was to simulate the Point-In-Time Grid-Based illumination analysis for the three designs at a specific time and date (21st of June at 12:00pm). The analysis shows the significant impact of using double skin instead of static and glazed façade as a third design skin.

TABLE 3. Illumination grid values for programmable, kinetic, and static façades, calculated for June 21st at 12:00pm using the Ladybug and Honeybee plugins.

View	Programmable	Kinetic	Static
Isometric View of Point-In-Grid-Based Illumination Simulation on 21 June, 12 PM (Using Ladybug and Honeybee)			
Plan View of Point-In-Grid-Based Illumination Simulation on 21 June, 12 PM (Using Ladybug and Honeybee)			

6. Discussion

The illumination distribution obviously differentiates between the three designs where the static prototype design has the maximum impact values in the front area of the room causing glare. The kinetic façade shows the better solution to distribute light throughout space, as well as the programmable skin which has different features. The responsive double skin acts as adaptive solar shading.

Due to the morphological design capabilities, the unit transformation changes the light distribution by diffusion and reflection of sun rays, as shown in Figure 11, utilizing Ladybug and Honeybee simulation tools. The results show the light transmission capability between the two-design morphological types. The environmental simulation for daylight, radiation, and point-in-time illumination, shows through its distribution the significant impact of using a programmable double skin.

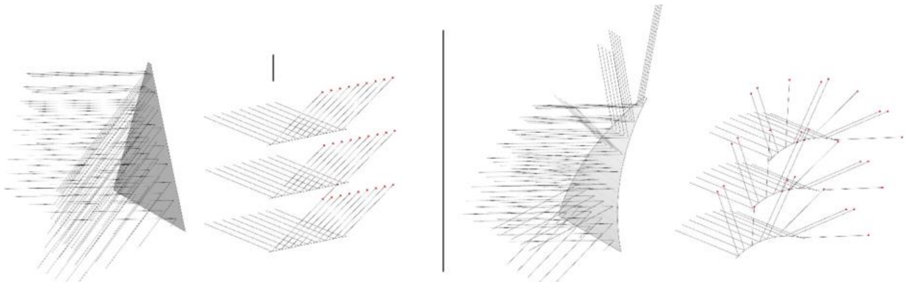


Figure 11. Light ray distribution and morphology in programmable and kinetic skins: *Left*: Rotational transformation for simple kinetic motion, *Right*: Bending transformation reflecting programmable material morphology.

7. Conclusion

The first part of the research explores the use of the Albizia Lebbeck wood samples, as a hygromorphic programmable material. The material shows a considerable reaction to moisture with different morphological transformation capabilities due to its fibrous characteristics. The material also demonstrates the importance of utilizing low-cost natural substances as architectural elements to achieve sustainability principles.

Multiple experiments were conducted on the Albizia Lebbeck material samples. The experiments show the unit transformation with a high deflection angle. Applying the same experiment procedures on a large-scale triangular unit sample (50cm width x 50cm height x 0.5cm thickness) shows the material's quick response to humidity and the ability of light transmission through the element after deformation.

Validation was conducted for an office space using three samples: Albizia Lebbeck programmable skin, kinetic skin, and static skin. Environmental simulations illustrate the significant difference between the three products regarding light transmission. Daylight and radiation were simulated and analyzed annually, while point-in-time illumination occurred in the peak time of summer. These simulations demonstrate the impact of using the programmable skin prototype in the scope of the unit's ability to diffuse light rays without causing glare or high levels of illumination in interior spaces.

At the level of unit creation, the bending transformation demonstrates the ability of the skin to distribute illumination in the interior of the space in contradiction with planar skin surfaces. Hence, the transformation strategy plays a vital role in light transmission and penetration, thus improving space performance to reach human comfort. Finally, utilizing the Albizia Lebbeck material as a double programmable skin can improve the spatial performance in terms of light penetration and distribution, as well as the cost and sustainability benefits due to its natural, low cost, and environmentally friendly material characteristics.

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EXPLORING LOW-COST SENSORS FOR INDOOR AIR QUALITY (IAQ) MONITORING: A REVIEW OF STATIONARY AND MOBILE SENSING SYSTEMS

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Abstract. Indoor air quality (IAQ) is considered a crucial aspect of building health and occupant well-being, especially as occupants spend 90 percent of their time indoors. Different factors impact the concentration of air pollutants and air quality in indoor spaces including inadequate ventilation, emissions from building materials and furnishings, and biological contaminants. Thus, indoor air quality (IAQ) needs to be carefully monitored and controlled as a building operation priority to maintain healthy indoor environments. The IAQ monitoring can be accomplished using stationary and mobile sensors, each of which option offers advantages and disadvantages. This project reviews recent studies employing stationary and mobile monitoring sensing systems to investigate and compare the characteristics of these monitoring sensing systems targeting air quality in interior architectural spaces. A thorough assessment of the characteristics of IAQ sensing systems was conducted, encompassing factors such types, availability, spatial and temporal monitoring coverage, accuracy, and precision in IAQ measuring, and detection potential for various pollutants. The results will provide building professionals with the needed insight to make informed decisions when planning for IAQ monitoring.

Keywords: *Indoor environmental quality (IEQ), Indoor air quality (IAQ), Sensors, Arduino, Stationary sensing, Autonomous mobile sensing, Robotic sensing, Machine learning.*

ملخص. تعتبر جودة الهواء الداخلي (IAQ) جانبًا مهمًا لبناء صحة ورفاهية المستخدمين، خاصة وأنهم يقضون ما يقارب من 90 بالمائة من وقتهم في البيئات الداخلية. هناك عوامل مختلفة تؤثر على تركيز ملوثات الهواء ونوعية الهواء في الأماكن الداخلية بما في ذلك عدم كفاية التهوية، الانبعاثات من مواد البناء والمفروشات، والملوثات البيولوجية. وبالتالي، يجب مراقبة جودة الهواء الداخلي والتحكم فيها بعناية كأولوية تشغيلية للمبنى للحفاظ على بيئات داخلية صحية. يمكن إجراء مراقبة جودة الهواء الداخلي باستخدام أجهزة الاستشعار الثابتة والمتحركة، ولكل خيار منها مزايا وعيوب. يستعرض هذا المشروع الدراسات الحديثة التي

EXPLORING LOW-COST SENSORS FOR INDOOR AIR QUALITY (IAQ) MONITORING: A REVIEW OF STATIONARY AND MOBILE SENSING SYSTEMS

تستخدم أنظمة استشعار المراقبة الثابتة والمتحركة لدراسة ومقارنة خصائص هذه الأنظمة التي تستهدف جودة الهواء في المساحات المعمارية الداخلية. تم إجراء تقييم شامل لخصائص نظامي استشعار الجودة الداخلية (الثابت والمتحرك)، يشمل عوامل مثل الأنواع، والتوافر، وتغطية المراقبة المكانية والزمانية، والدقة في قياس الجودة الداخلية، وإمكانية الكشف عن الملوثات المختلفة. ستزود النتائج محترفي البناء بالرؤية اللازمة لاتخاذ قرارات مناسبة عند التخطيط لمراقبة الجودة الداخلية.

الكلمات المفتاحية: جودة البيئة الداخلية (IEQ)، جودة الهواء الداخلي (IAQ)، أجهزة الاستشعار، الأردوينو، الاستشعار الثابت، الاستشعار المتنقل المستقل، الاستشعار الآلي، التعلم الآلي.

1. Introduction

In recent years, the monitoring and improvement of indoor environmental parameters to create a healthy and balanced indoor built environment have gained significant importance. This growing awareness has led to an increased demand for new technologies and robotic features to enhance the harmonious situation of indoor environmental factors (Kim, Schiavon and Brager, 2018).

Indoor air quality has gained significant attention, particularly in the aftermath of the COVID-19 pandemic, due to its impact on the health and well-being of indoor occupants. Compared to outdoor pollution, indoor pollution is significantly more likely to affect the lungs (Zhang and Smith, 2003). The World Health Organization has identified several air pollutants, such as particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulfur dioxide, as major concerns associated with respiratory diseases, increased mortality, and morbidity (WHO). Burning fuels for various purposes, including cooking, heating, and lighting, is a primary source of indoor air pollutants (Manisalidis *et al.*, 2020).

Indoor environment quality (IEQ) encompasses several components, including thermal comfort, air quality, acoustic comfort, and visual comfort (Piasecki, Kostyrko and Pykacz, 2017). For the purpose of this research paper, the focus will be on indoor air quality (IAQ), as it represents a crucial aspect of IEQ. The indoor environment has a profound impact on occupants' productivity, well-being, health, and satisfaction, regardless of whether they spend their time in buildings or urban spaces (Guoyi Hou, 2016). Despite technological advancements, we still struggle to address indoor environmental quality issues. This is because the parameters that influence IEQ are complex and can be affected by a variety of factors. As a result, it can be challenging to capture accurate data for all relevant aspects of IEQ. However, by adopting a monitoring approach and selecting the most relevant and available data, we can improve air quality, thermal models, and management systems. For example, J. Kim et al. (2018) showed that by monitoring, recording, and observing data, it is possible to improve air quality and thermal models and management systems (Kim, Schiavon and Brager, 2018).

Monitoring air quality can help us identify areas where pollutants are concentrated and take steps to reduce them. For example, monitoring can help us identify areas where smoking is taking place or where there are high levels of dust or pollen.

Surveys can provide valuable feedback on current thermal perception, but they can be burdensome for occupants and the accuracy of the collected data may be debatable. Alternatively, wearable devices or infrared cameras with internet connectivity can monitor occupants' physiological indicators, such as heart rate, skin temperature, and metabolic activity (Yoon DW, Sohn JY, and Cho KH., 1999; Frontczak and Wargocki, 2011; Enescu, 2017). Additionally, individual behavioral data, including location, movements, and heating and cooling activities, can be collected using various devices such as occupancy sensors, pedometers, GPS trackers, and smart thermostats (Kim, Schiavon and Brager, 2018). By monitoring IEQ, we can gain a better understanding of the factors that influence it and take steps to improve the quality of our indoor environments.

The importance of providing a balanced indoor environment and effective IEQ management systems to meet occupants' comfort needs and promote a healthy and balanced indoor built environment has been acknowledged by researchers. Achieving optimized IAQ and IEQ requires an integrated environmental model that can handle the complexity of indoor environmental parameters. The integration of the Internet of Things (IoT), intelligent sensors, and robotics capabilities, along with machine learning algorithms, can facilitate the realization of a harmonious and healthy indoor environment. This has led to the development of two approaches: stationary sensing systems and mobile sensing systems. Each approach offers unique advantages and limitations in monitoring indoor environmental factors.

The work explores the role of low-cost sensors in different -monitoring systems, data acquisition, spatial and temporal distribution, collected data accuracy, and the practicality of these two types of systems. The research project consists of two phases. Phase one will study stationary monitoring sensing systems, analyzing their types, accuracy, precision, and pollutant detection capabilities by reviewing existing studies. Phase two will shift to mobile monitoring sensing systems, examining aspects like portability, user-friendliness, and real-time data. The project will then compare both types to identify their strengths and weaknesses. The project is expected to provide a comprehensive understanding of stationary and mobile monitoring systems for IAQ, which will help building professionals make better decisions when selecting and utilizing IAQ monitoring technology.

2. Sensing systems and technologies:

Two types of sensing systems have emerged as monitoring systems for indoor air quality and thermal comfort. These two systems are stationary sensing systems and mobile sensing systems. These systems play a crucial role in understanding and managing indoor air quality (IAQ), thermal comfort, and other environmental parameters. While the prevailing practice leans towards stationary sensing systems. However, with the advancement of the Internet of Things and robotics, there is a growing interest in exploring the potential of mobile sensing systems and their integration with the Internet of Things (IoT).

2.1. STATIONARY SENSING SYSTEMS

The current methods used for assessing indoor air quality (IAQ) and thermal comfort primarily rely on the installation of stationary environmental sensors in specific locations. However, these practices have certain limitations that need to be addressed. One major drawback is the high cost associated with deploying multiple sensors throughout space. Not only does this involve a significant initial investment, but it also requires ongoing maintenance and calibration to ensure accurate readings (Zhang *et al.*, 2013; Bulińska, Popiołek and Buliński, 2014). Another limitation of the stationary sensor approach is its limited spatial coverage. Since the sensors are fixed in specific locations, they can only provide data from those points, leaving gaps in our understanding of indoor air quality (IAQ) and thermal comfort across the entire area (Jeon *et al.*, 2018; Jin, Bekiaris-Liberis, *et al.*, 2018). This lack of comprehensive coverage hinders our ability to capture variations in temperature, humidity, air quality, and other important factors that impact indoor conditions (Zhang *et al.*, 2013; Ramos *et al.*, 2015; Jin, Bekiaris-Liberis, *et al.*, 2018; Geng *et al.*, 2022).
Furthermore, stationary sensors require regular maintenance and calibration to ensure their accuracy and reliability. This maintenance process adds to the overall cost and can be time-consuming, especially in larger buildings with numerous sensors. Calibration is crucial to ensure that the sensors provide consistent and precise measurements over time, but it can be a complex task that requires specialized knowledge and equipment (Yang *et al.*, 2021).
Given these challenges, it became essential to explore alternative approaches that can overcome the limitations of current practices in indoor air quality (IAQ) and thermal comfort sensing (Berawi *et al.*, 2023). This exploration involved seeking cost-effective solutions that offer comprehensive spatial and temporal coverage while minimizing maintenance and calibration

requirements. Thus, the concept of mobile sensing systems has emerged and researchers have been exploring the possibilities of improving the accuracy and efficiency of assessing IAQ and thermal comfort in various indoor environments, especially with the advancement in technology (Plageras *et al.*, 2018; Xu *et al.*, 2020).

2.2. MOBILE SENSING SYSTEMS

Mobile sensing systems are a relatively new and evolving approach to indoor environmental monitoring. These systems leverage the capabilities of mobile robots, wearable devices, or even personal mobile devices equipped with sensors to collect real-time data on different environmental factors. By moving through different areas of a building, mobile sensing systems provide spatial-temporal data that can complement the information obtained from stationary systems. They offer the ability to track the movement of occupants, detect changes in environmental conditions, and even identify sources of pollution or discomfort (Jin, Bekiaris-Liberis, *et al.*, 2018; Dong *et al.*, 2019; Wei *et al.*, 2020).

Mobile sensing systems offer several advantages over their stationary counterparts. They are less susceptible to vandalism or tampering since they are not fixed in one location. They can cover a larger spatial area, including hard-to-reach or inaccessible spaces, providing a more comprehensive spatial coverage of the indoor environment. While stationary systems offer local real-time monitoring (i.e., live monitoring of data for a certain spatial point in an architectural space), mobile systems can provide real-time data for their navigation route. Choosing the navigation route to maximize the spatial coverage can enable more timely responses and interventions to maintain optimal IAQ and thermal comfort in open indoors space where limited opportunities exist for installing stationary system. This provides greater potential for applications in indoor spaces due to flexibility, low-cost infrastructure, and autonomy(Jiang *et al.*, 2011; Xiang *et al.*, 2013; Jin, Liu, *et al.*, 2018). However, there are several challenges associated with mobile sensing systems. One major challenge is the higher cost of installation and maintenance of mobile systems compared to stationary systems. The need to ensure the accuracy and reliability of data collected from mobile sensors adds complexity to the process. Factors such as sensor calibration, precise positioning, and data fusion must be carefully addressed to obtain trustworthy measurements (Jiang *et al.*, 2011; Jin, Liu, *et al.*, 2018; Dong *et al.*, 2019; Geng *et al.*, 2022).

Furthermore, integrating mobile sensing systems with existing building management systems and IoT infrastructure requires careful planning and consideration of compatibility issues. The seamless integration of these systems is crucial to ensure smooth data flow and effective utilization of the collected information (Xiang *et al.*, 2013; Desogus *et al.*, 2021). Another important drawback of mobile sensors is their susceptibility to drift error. Drift occurs when sensor readings gradually deviate from the expected or accurate values over time. This can lead to inaccuracies in measurements and potentially compromise the reliability of the collected data. To mitigate drift, regular calibration and maintenance of the sensors are necessary (Xiang *et al.*, 2013). However, it is worth noting that advancements have been made in the development of pre-calibrated IoT sensors. These sensors come pre-calibrated from the manufacturer, reducing the likelihood of drift and improving the overall accuracy of the measurements.

2.3. REVIEW PAPERS ON SENSING SYSTEMS

For the reviewed papers, we gathered articles from respected databases, Web of Science and SCOPUS, known for indexing major journals in our subject area. To ensure the inclusion of the most current research, we specifically considered articles published between 2013 and 2023. Our selection process was methodical, involving the use of key terms such as "Internet of Things (IoT)," "Indoor environmental quality (IEQ)," "Thermal comfort," "Indoor air quality (IAQ)," "Sensors," "Arduino," "Autonomous mobile and robotic sensing," and "Machine learning" for filtering.

Our inclusion criteria focused on articles that explored the integration of indoor built environment monitoring and sensing with IoT or IoRT. Through rigorous searching within titles, abstracts, and published keywords, we identified a total of 354 articles published since 2013. Among these, 62 articles were directly pertinent to our topic, with a noteworthy 68% (42 articles) of them being published between 2019 and 2023, indicating a growing interest in this subject over recent years.

The following Table 1 encompasses part of these research articles, they explore various parameters, including air pollutants, CO2 concentration, thermal comfort, VOCs, temperature, relative humidity, and particulate matter (PM), by utilizing one of the sensing systems.

TABLE 1. Literature review papers.

Authors	Data collection	Type of System (stationary / mobile)	Research Focus
(Steinle, Reis and Sabel, 2013)	Air pollutants	Stationary	Comparing tracking systems (e.g., GPS) and fixed sensors.
(Yang *et al.*, 2014)	CO2 concentration	Stationary	This research integrates pervasive computing, artificial intelligence, embedded systems, distributed computing, and cognitive networks
(Kim, Chu and Shin, 2014)	(O3, PM, CO, NO2, SO2, VOC and CO2) , temperature and humidity	Stationary	Focuses on real-time monitoring of various gas pollutants. The study highlights the trade-offs between MOS-type gas sensors and electrochemical/optical sensors.
(Folea and Mois, 2015)	CO2, Air temperature and relative humidity	Stationary	Provides an approach for ambient monitoring using battery-powered low-power sensors. It shows that using low-power ambient sensors and ultra-low-power Cozir CO2 sensors could help achieve low-power consumption in ambient monitoring.
(Salamone *et al.*, 2016)	Thermal	Stationary	Optimizing indoor thermal comfort and energy consumption through direct interactions with the heat pump.
(Marques and Pitarma, 2016)	Air temperature , moistness, carbon monoxide, carbon dioxide	Stationary	This work suggests an indoor Air quality system enables real-time data access for doctors, supporting medical diagnostics by providing information about the indoor environment's Air quality.
(Qian *et al.*, 2016)	VOC	Mobile	Combines environmental mapping and IAQ data, through a gas distribution map, aligning with the estimated occupancy grid map obtained from a laser scanner sensor.
(Ray, 2016)	Temperature, relative humidity	Stationary	A prototype system has been developed using the novel architecture to measure the thermal comfort of indoor occupants.
(Kang and Hwang, 2016)	CO, Temperature, Relative Humidity, VOC, PM	Stationary	Suggests a real-time CAQI (Comprehensive Air Quality Index) for indicating indoor air quality indication using low-cost sensors and color LED display.

(Konis and Annavaram, 2017)	Air temperature and relative humidity	Mobile	The paper proposes a scalable approach that utilizes personalized comfort models to achieve the potential for comfort and energy savings through data-driven thermal management.
(Mahanth and Karishma, 2017)	CO and CO2	Stationary	In this research, the experiments conducted on the proposed system confirmed its capability to detect indoor CO and CO2 levels conveniently.
(Jin *et al.*, 2018)	CO2, Air temperature and relative humidity, VOC	Stationary& Mobile	This research introduces a data-efficient spatio-temporal (ST) interpolation method that captures local and global trends, creating an informative visualization of Indoor Environmental Quality (IEQ).
(Benammar *et al.*, 2018)	CO2, CO, SO2, NO2, O3, Cl2, CO, Temperatur e, Relative Humidity	Stationary	The paper presents an end-to-end integrated Indoor Air Quality Monitoring (IAQM) system measuring various pollutants, emphasizing the gateway's role in data processing and dissemination to users through a web server.
(Marques, Roque Ferreira and Pitarma, 2018)	Particulate matter	Stationary	The paper introduces iDust, an Internet of Things (IoT) system for real-time PM monitoring. It offers a Web dashboard for data visualization and remote notifications, enabling building managers to plan interventions for improved Indoor Air Quality (IAQ).
(Moiş *et al.*, 2018)	Particulate matter, VOC	Stationary	This research goal is to achieve energy-efficient autonomous operation of Air quality sensors and represents an initial step for scalable low-cost systems with wireless sensors.
(Taştan and Gökozan, 2019)	CO2, CO, PM10, NO2 tempe rature and humidity,	Stationary	This research proposes an e-nose, a real-time mobile Air quality monitoring system, capable of measuring various Air parameters such as CO2, CO, PM10, NO2, temperature, and humidity, using a do-it-yourself approach.
(Marques and Pitarma, 2019)	CO2, Air temperature and relative humidity,	Stationary	Introduce an IoT architecture called iAQ Plus (iAQ+) that enables real-time data collection of Indoor Environmental Quality (IEQ) in laboratory settings.

(Mylonas *et al.*, 2019)	CO_2, Air temperature and relative humidity	Stationary	This research aims to quantify the impact of sensor capabilities and limitations on HVAC system operation, energy usage, and indoor environment.
(Cheng, Tseng and Hildemann, 2019)	PM2.5	Stationary & Mobile	The study investigated the potential of a mobile monitoring method to map PM2.5 distributions in a one-bedroom apartment. The method utilized ultrasound localization with collocated research-grade and low-cost sensors (SidePak and PTQS).
(Quan Pham, Rachim and Chung, 2019)	CO_2, Air temperature and relative humidity, VOC	Stationary	This research suggests an innovative indoor environment monitoring system utilizing EMI-free bidirectional visible light communication technology.
(Cashikar, Li and Biswas, 2019)	PM2.5	Mobile	The AAQRL-ROBOPM, an affordable, programmable, and agile mobile sensor module, was demonstrated to perform PM concentration sampling through manual or autonomous control.
(Marques, Ferreira and Pitarma, 2019)	CO_2	Stationary	The research introduces the iAirCO2 system, an IoT-based solution for real-time CO_2 monitoring. It includes a hardware prototype for ambient data collection.
(Sung, Hsiao and Shih, 2019)	Air temperature and relative humidity	Stationary	Monitoring system through the Internet of Things (IoT)
(Trilles *et al.*, 2019)	CO_2, Air temperature and relative humidity, VOC	Stationary	The research proposes a validation of a particulate matter (PM) sensor (HM-3301) in indoor and outdoor environments to study PM2.5 and PM10 concentrations.
(Folea and Mois, 2020)	BLE	Stationary	Testing Bluetooth Low Energy (BLE)
(Agrawaal, Jones and Thompson, 2020)	Particulate matter- more focus on outdoor	Stationary	The aim of the research is to enhance understanding of human exposure to PM pollution by establishing and implementing a network of multiplexed, portable PM sensors.
(Mahbub, Hossain and Gazi, 2020)	lighting, CO_2, Air temperature and relative humidity, VOC	Stationary	The research involved developing a prototype with an algorithm to monitor indoor conditions, including lighting, temperature, humidity, CO_2, and smoke detection, aiming for energy efficiency and self-sufficiency.

(Coulby *et al.*, 2021)	CO2, VOC, Air temperature and relative humidity, VOC	Stationary	This study presents insights into an IoT-enabled multimodal device for IEQ monitoring based on MEMS technology. It explores inter-device variability and validity compared to reference standard sensors.
(Floris *et al.*, 2021)	CO2, VOC, Air temperature and relative humidity, VOC	Stationary	Particularly focus on the investigation of the relationship between the indoor environmental state of the building and the building occupancy information.
(Luo, Hong and Pantelic, 2021)	CO2, PM2.5, Air temperature	Stationary	Demonstrate the use of an IoT environmental sensing network both outdoors and indoors.
(Yang *et al.*, 2021)	CO2	Stationary & Mobile	This research investigates directing mobile sensing with one sensor node to monitor indoor air quality (IAQ) along pre-planned paths using the SLAM algorithm.
(Choi, Jung and Cho, 2021)	CO, CO2, PM2.5, PM10, TVOC, H2S, NO2, and NH3,	Stationary	The study compares the existing method with the proposed method by employing five univariate imputation methods and five multivariate imputation methods.
(Peladarinos *et al.*, 2021)	Particulate Matter	Stationary	Introduces an open-source platform architecture and describes the development of a Long Range (LoRa) based sensor network for monitoring indoor air quality (IAQ) and particulate matter (PM).
(Geng *et al.*, 2022)	Air temperature and relative humidity, VOC	Mobile	The paper presents a robot-based mobile system for high-resolution temperature monitoring. Experiments compare mobile sensing with dense stationary network.
(Troncoso-Pastoriza *et al.*, 2022)	CO2, Air temperature and relative humidity, VOC	Stationary & Mobile	The paper deploys the platform with wall-mounted devices and a mobile device to gather data from different room positions. After training, the mobile device is removed, and accurate results continue without human intervention.
(Salamone *et al.*, 2022)	Air temperature and relative humidity, VOC	Stationary	Developed a system to record data from seven thermohydrometers and evaluated their performance against a reference device in a controlled environment to assess the performance of low-cost sensors.

(Calvo *et al.*, 2022)	CO2, VOC, Air temperature and relative humidity	Stationary	This paper introduces a scalable IoT architecture based on the edge–fog–cloud paradigm for monitoring the Indoors Environmental Quality (IEQ) parameters in public and private buildings.
(Al-Okby, Roddelkopf, *et al.*, 2022)	VOC, NO2	Stationary	In this research a commercial MOX gas sensor, SGP41, was embedded in an IoT environmental sensor node for hazardous gas detection and alarm.
(Riffelli, 2022)	CO2, Air temperature	Stationary	This paper presented a wireless IEQ logger with a DIY philosophy.
(Al-Okby, Neubert, *et al.*, 2022)	TVOC	Stationary	This research investigates the performance of gas sensors SPG30 and SPG40to determine the best parameter between TVOC and IAQ-index for future hazardous gas detection.
(Hawchar, Ould and Bennett, 2022)	CO2	Stationary	This research investigates the dynamic concentration of CO2 over the course of various working cycles.
(Kuncoro, Adristi and Asyikin, 2022)	PM2.5	Stationary	Smart wireless particulate matter sensor node for measuring and monitoring indoor PM2.5 and PM10 concentrations levels.
(Marzouk and Atef, 2022)	CO2, PM, Air temperature and relative humidity	Stationary	This research introduces an IoT-based system for real-time indoor air quality (IAQ) monitoring, combining microcontrollers and electronic sensors to collect various indoor readings and evaluate IAQ.

Table 1 emphasis that numerous research studies have shown that existing methods for indoor environmental quality (IEQ) sensing rely heavily on stationary sensors that are installed in specific locations. However, this approach is plagued by several limitations, such as high costs due to the need for multiple sensors and inadequate spatial coverage.

Furthermore, the installation, calibration, and maintenance of stationary sensing systems can be complex and expensive, which poses challenges in data analysis and delayed sensing. Despite attempts to use mobile sensing as a surrogate solution for stationary sensing, the two techniques have their respective benefits and drawbacks, and attempts to integrate them have been inadequate. Nevertheless, combining both systems could potentially bring more significant benefits to sensing technology. Various works have investigated this approach, including those by Jiang et al. (2011), Heinzerling et al. (2013), Jin et al. (2018), Wu & Liu (2018), Yang et al. (2021), and Geng et al. (2022).

A current concern is the integration of IoT and IEQ to evaluate indoor environments. To reduce costs, minimizing the number of IEQ monitoring devices is essential. However, this can be a challenging task as new monitoring equipment must be validated scientifically, which requires the use of costly and established equipment.

Coulby et al. (2020) noted this difficulty. Notably, the studies selected did not address the challenge of collecting data in built environments. Nevertheless, they demonstrated the benefits of integrating IoT for building control and reducing energy consumption (Coulby, Clear, Jones, & Godfrey, 2020). However, few studies have focused on people's comfort, and more research is necessary to investigate the human-data interaction aspect, as it is not feasible to completely exclude individuals from building control. Broday & Gameiro da Silva (2022) highlighted the importance of diving deeper into this aspect (Broday & Gameiro da Silva, 2022).

In order to get a holistic picture of IEQ, multiple devices are required since many different factors determine it. Therefore, indoor spaces are often measured from a single location, which reduces the spatial density of IEQ measurements and limits the inferences about spatially distributed individuals' health and well-being.

For gains in spatial density and longitudinal monitoring, researchers believe it may be beneficial to sacrifice precision and accuracy of measurement (Coulby et al., 2021).

Another limitation of research-grade monitoring devices is the deficiency in connecting to a cloud platform. The collected data will be stored internally, limiting a real-time monitoring approach. Thus, the new approach of using Low-cost sensors can overcome those limitations with their ability to connect to IoT-cloud platforms (Coulby, Clear, Jones, & Godfrey, 2020; Coulby, Clear, Jones, Young, et al., 2020; Coulby et al., 2021).

The following Table 2 presents a comparison between stationary and mobile sensors in terms of measurement acquisition, temporal distribution, spatial distribution, type of map network, size, monitoring time, and space/building type. These points of comparison in Table 2 are based on the outcomes of the literature review.

The use of stationary sensors allows accurate measurement acquisition with fixed schedules at the same sensing point, but it lacks a cost-effective solution to cover a broader spatial distribution due to infrastructure investment costs and limited sensing range. On the other hand, mobile sensors offer more flexibility in sensing points with IoT and Wireless Sensor Networks, leading to improved spatial resolution and coverage in larger spaces. However, they are more suitable for short-term monitoring due to the limitations of continuous movement in small spaces.

TABLE 2. Sensing systems characteristics.

Systems characteristics	Stationary sensors	Mobile sensors
Measurement acquisition	Acquires data, and the corresponding measurement to the same timestamps position.	Collects data, the real-time position, and mapping according to different active timestamps
Temporal distribution	Accurate Fixed schedule for the same sensing point.	Flexible schedule for different sensing point through using Internet of Things (IoT) and Wireless Sensor Networks
Spatial distribution	lacks a cost-effective solution: install multiple IEQ sensors at different positions. - Firstly, more sensors mean more infrastructure investment costs. - Secondly, IEQ sensors can only cover a small range of space around their installation location as they are fixed in their installation locations, (Several practical factors influence the actual selection of sensor installation positions, such as the requirement that the sensor be connected to an external power supply and not disrupt normal building operations. - Another concern is that placing sensors near the perimeter of large spaces, which is a common practice, may not accurately represent the actual concentrations of people in the building. This could result in incomplete and inadequate IEQ data, even with multiple stationary sensors, unless we carefully plan a representative sampling strategy.	Can improve the spatial resolution and flexibility of IEQ monitoring.

	- Furthermore, the stationary sensors can only passively collect data. They are unable to actively respond to changes in the environment, potentially missing critical fluctuations in IEQ conditions that require immediate attention.	
Type of map network	Establish a static network with specific predetermined points	Establish a dynamic network
Size	Local sensing (Fixed points)	Broader sensing (Different points)
Monitoring time	A most reliable and convenient method for long-term IEQ monitoring, though the spatial resolution is usually far from satisfactory	Can obtain IEQ maps with better spatial resolution, but this is a short-term solution because the robot cannot run continuously in the long term.
Space / Building Type	A stationary sensing system can monitor IEQ more efficiently in a small space. Accurate readings.	The robotic mobile sensing system can monitor IEQ more efficiently in a larger space (more coverage). In small spaces, this system might face a limitation in movement.

In conclusion, Table 2 offers a comprehensive comparison between stationary and mobile sensors in the context of IEQ monitoring. This evaluation underscores the distinctive advantages and limitations of each approach. Stationary sensors excel in providing accurate, long-term data from fixed points, making them suitable for consistent monitoring in smaller spaces. However, their limited spatial coverage, inability to adapt to dynamic environments, and lower spatial resolution can pose challenges in larger or evolving settings. On the other hand, mobile sensors offer flexibility, better spatial resolution, and adaptability in larger spaces. They enable real-time data collection and mapping, albeit often for shorter durations due to mobility constraints. The choice between stationary and mobile sensors hinges on the specific requirements of IEQ monitoring projects, with each approach offering unique benefits tailored to different scenarios.

Additionally, integration with indoor space characteristics is essential to align the selection of monitoring systems with the specific requirements of the indoor space and the activities conducted within it. Factors such as room size, layout, and usage patterns should guide the decision-making process. Ultimately, the goal is to optimize IAQ and thermal comfort while considering the dynamic nature of the indoor environment. By integrating the dimensions and typology of indoor spaces with the advantages and challenges of stationary and mobile sensing systems, a more tailored and effective monitoring approach can be established.

Stationary sensing systems, which rely on fixed environmental sensors, are often well-suited for specific types of indoor spaces. Conversely, mobile sensing systems, which utilize robots, offer unique advantages in larger or more complex indoor spaces. These systems can adapt to the dynamic nature of such environments, where activities and occupancy may vary throughout the day.

Moreover, the nature of activities within the indoor space can influence the choice of monitoring method. Thus, the typology of the indoor space must be considered. For instance, in a laboratory setting where air quality is critical to experiments, or in commercial buildings with distinct zones, such as conference rooms and workstations, different types of buildings associated with different activities can impact the sensing data and the required sensing to help maintain optimal conditions within each zone.

This study is part of an ongoing Ph.D. project, contributing to the existing literature review on the topic of indoor air quality monitoring. It focuses on providing a logical understanding of strategies and approaches to the Internet of Robotics of Things and indoor air quality (IoRT-IAQ.

5. Conclusion

The outcomes presented in Tables 1 and 2 offer a comprehensive view of IEQ and IAQ monitoring systems, both stationary and mobile. Table 1 showcases a diverse range of research endeavors, each tailored to specific parameters and research focuses. It provides insights into the evolution of IEQ monitoring, from stationary sensors optimizing IAQ, thermal comfort to mobile sensors combining environmental mapping and data distribution.

On the other hand, Table 2 dissects the characteristics of these systems, shedding light on their strengths and limitations. It underscores the precision and stability of stationary sensors, which excel in small spaces but may grapple with spatial coverage. In contrast, mobile sensors introduce flexibility and spatial granularity, though they are typically deployed for shorter durations. The diverse range of findings presented in these tables emphasizes the complexity of IEQ monitoring. When making choices regarding sensor selection and deployment, it's crucial to have a profound grasp of the particular requirements and limitations of the environment under examination, while also considering the desired level of spatial precision and temporal scope.

While both stationary and mobile sensing systems have demonstrated significant advantages, it is important to acknowledge that there are still limitations in fully understanding IEQ and IAQ using these approaches.

One area that requires exploration is the familiarity of stationary sensors with the environment. Understanding how these sensors interact with indoor space and their ability to accurately define the source of pollution is crucial for reliable IEQ assessment. Additionally, there is a need to investigate and incorporate more indoor air quality (IAQ) parameters into the sensing systems to expand their potential applications and provide a more comprehensive understanding of IEQ.

Moreover, it is worth exploring the possibility of connecting the sensing systems with building automation systems. Integration with automation technology can enhance the efficiency and effectiveness of sensing, allowing for intelligent decisions and direct actions to improve the indoor environment. This can be achieved through the application of machine learning algorithms that enable data analysis and real-time responses to change IEQ conditions.

It is important to note that existing methods heavily rely on stationary sensors, which come with limitations such as high costs and inadequate spatial coverage. The installation, calibration, and maintenance of these systems can be complex and expensive, leading to challenges in data analysis and delayed sensing. While attempts have been made to use mobile sensing as an alternative, there is still room for improvement in integrating both approaches to maximize the benefits of sensing technology.

By addressing these areas of concern and leveraging the strengths of both stationary and mobile sensing systems, it is possible to enhance our understanding of indoor environmental quality and pave the way for more effective and efficient sensing technologies in the future.

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URBAN PERFORMANCE

Parametric digital process for simulation and analysis of occupancy in regional centralities area of Belo Horizonte

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Abstract. The present study aims to explore the urgent issue of urban expansion and its impact on cities, with a specific focus on the regional centrality areas of Belo Horizonte. The main contribution of this work is the development of a parametric model to assess the environmental impact of intensive occupation in these areas and verify their compliance with sustainable development criteria. The study directly addresses the challenges arising from rapid urbanization, offering a digital approach to analyze and simulate the impact of intensive urban occupation in the regional centrality areas. As a methodology, we used georeferenced data, the Grasshopper parametric modeling software, and the Ladybug plugin for environmental simulations, effectively combining empirical information and computational tools to obtain significant results related to the impacts resulting from the proposed densification.

Keywords: *Urban Data Analysis; Urban Design; Parametric Urbanism; Sustainability; Parametric Modeling.*

ملخص. تهدف هذه الدراسة إلى استكشاف القضية الملحة للتوسع الحضري وتأثيرها على المدن، مع التركيز بشكل خاص على المناطق المركزية الإقليمية في بيلو هوريزونتي. المساهمة الرئيسية لهذا العمل هي تطوير نموذج حدودي لتقييم الأثر البيئي للاحتلال المكثف في هذه المناطق والتحقق من امتثالها لمعايير التنمية المستدامة. تتناول الدراسة بشكل مباشر التحديات الناشئة عن التحضر السريع، وتقدم منهجًا رقميًا لتحليل ومحاكاة تأثير الاحتلال الحضري المكثف في المناطق المركزية الإقليمية. كمنهجية، استخدمنا البيانات الجغرافية المرجعية، وبرنامج النمذجة البارامترية Grasshopper، والبرنامج الإضافي Ladybug لعمليات المحاكاة البيئية، والجمع بشكل فعال بين المعلومات التجريبية والأدوات الحسابية للحصول على نتائج مهمة تتعلق بالتأثيرات الناتجة عن التكثيف المقترح.

URBAN PERFORMANCE: PARAMETRIC DIGITAL PROCESS FOR SIMULATION AND ANALYSIS OF OCCUPANCY IN REGIONAL CENTRALITIES AREA OF BELO HORIZONTE

الكلمات المفتاحية: تحليل البيانات العمرانية، التصميم الحضرى، العمران البارامترى، النمذجة البارامترية.

1. Introduction

Urban expansion has been a common characteristic of the urbanization process in many cities, resulting in issues such as low connectivity, underdeveloped infrastructure, and socioeconomic inequality. On the other hand, the compact city is seen as a more sustainable and inclusive alternative. In this context, the Belo Horizonte Master Plan (2019) establishes regional centrality areas as priority zones for population increase and construction density, aiming for a more inclusive, safe, resilient, and sustainable city (UN, 2021). However, it's necessary to assess the environmental impact of this intensive occupation in centrality areas, which justifies the present research. Thus, the objective of this work was to build a parametric model for environmental analysis of Belo Horizonte's regional centrality areas, in order to evaluate the environmental impact of intensive occupation in these areas.

The methodology used in the research involved collecting georeferenced data from Belo Horizonte's regional centrality areas, available on the BHMaps portal. This data was imported into the parametric modeling software Grasshopper through the Urban plugin, which enables reading shapefile format files. The Ladybug plugin was used to conduct temperature and relative humidity simulations based on information from the EPW climate file. Sky View Factor (SVF) analyses were also performed to assess the amount of visible sky due to verticalization. Based on the simulation results, it was possible to generate comparative graphs between the current occupation scenario and the scenario proposed by the master plan.

With the obtained results, it was possible to critically evaluate the environmental impact of intensive occupation in these areas quantitatively and qualitatively, as well as to determine if the urban density parameters proposed by law meet measurable criteria of sustainable development. Additionally, the research sought to explore how new information design technologies can assist stakeholders in decision-making processes in urban planning.

2. Guidelines for Regional Centrality Areas

The current Master Plan approved for the city of Belo Horizonte (2019) through Municipal Law 11181/19 classifies as Regional Centrality Areas those portions of the territory where greater construction and population density are intended, promoting mixed use and concentration of economic activities. In addition to infrastructure requalification, the plan's intention is that interventions to be carried out in these areas represent opportunities for transforming the forms of appropriation, uses, and actions of centralities through interventions that express global objectives for a more inclusive, safe, resilient, and sustainable city (UN, 2018).

The idea of decentralization aims to shift from the formation of a monocentric city to the reconfiguration of a polycentric city, reducing dependence on the central area and the need for population displacement. Associated with urban and environmental improvement, the priority is to promote density and concentration of activities in areas with support capacity so that the largest number of people benefit from the actions resulting from redevelopment projects. According to Calthorpe (2001), the emergence of a new polycentric regional structure is a step towards reducing the increasing economic and social resource gaps between communities in metropolitan regions.

However, considering that very tall buildings can have negative effects such as distancing activities from street level and alterations in microclimate (SANCHES, 2020), it's necessary to analyze the occupancy patterns that will be generated by urban parameters with increased floor area ratio. It's also crucial to analyze how the distribution of green areas can contribute to improving density and verticalization conditions, as well as the direct effects on urban drainage metrics.

As guidelines to promote urban improvement and sustainability in these centrality areas, among others, the stimulation of socio-environmental solutions is established, foreseeing measures that seek to mitigate polluting events and encourage ecological solutions. Therefore, the main guidelines focus on promoting active mobility, expanding the availability of green public spaces, addressing lighting and public safety, encouraging cultural events and activities, and adhering to the principles of the smart city concept.

In this context, the Master Plan establishes that technology should be proposed as a "tool for the development of actions and agency among people who experience the daily life of the area, as well as for engagement and conscious use of public space" (BELO HORIZONTE MUNICIPALITY, 2021).

3. Technology and Urban Planning

The way we understand our cities is being transformed by georeferenced mapping; however, the way we design them is also influenced by the possibilities brought by emerging digital tools. As layers of digital data and information cover urban spaces, new approaches for studying and analyzing the built environment emerge. The relationship between cities and the use of digital technologies relates to the widely spread concept of smart cities, which emerged in the early 21st century due to the advancement of various digital tools of information technology and communication applied to urban management and planning. However, despite the term's widespread use in mass media and specialized literature, there are several contradictions and ambiguities associated with what has been produced.

The technocratic view of the smart city focuses solely on controlling the urban organism, highly strategic and data-driven, which has a limited impact, confined to an administrative device. Therefore, new perspectives of democratization, connected with data availability, can mature the concept to leverage the potential of algorithmic and parametric digital tools to assist in decision-making processes in urban design.

In digital practice, parametric processes combined with visualization and simulation possibilities have influenced architectural development since the 1950s, with the creation of experimental design systems based on systems theory and the possibilities brought by electronic computers. These have become primary tools to facilitate problem-solving logic and decision-making.

The possibility of interacting with the model through parameter manipulation allows simulation and evaluation of various scenarios, granting involved stakeholders the openness to mediate and interfere in the planning and urban management model. These tools align with what Ratti and Claudel (2015) propose, believing that in the contemporary digital paradigm, the architect's role is situated between top-down and bottom-up, where responsibility shifts from designing objects to constructing and orchestrating user-oriented processes. Although this theme is still nascent in academic research and governmental practice, some experiences have been undertaken in various national and international academic and professional contexts.

In academia, we can mention the work of the SENSEable City Lab at MIT (Massachusetts Institute of Technology), which promotes "urban imagination and social innovation through design and science" (SENSEABLE, 2021). The lab's mission is to anticipate urban transformations through technology and study them critically. To achieve this, the lab employs a transdisciplinary approach, considering industry, governments, as well as individual citizens and disadvantaged communities as participation agents.

In the professional realm, the commercial project City Zenith (2015) involves creating a platform based on gaming logic to assist agents (architects, urban planners, governments, entrepreneurs, builders, among others) in decision-making through visualization and simulation of master plans, urban restructuring plans, and infrastructure projects. The work of the French firm Reperáge Urbain, which created the Carticipe platform (2013), is also a participatory cartographic device designed by sociologists and urban geographers to promote debates and citizen consultations about a city or territory. The platform aims to systematically implement a local

"participatory ecosystem," offering methodological and human support to users.
Another reference project is the 3DEXPERIENCity platform (2013), offering a 3D view of the city and ongoing processes. Through various simulation and analysis tools, all stakeholders involved in urban design processes can understand and visualize the impact of potential decisions, aiming to break down governmental departmental boundaries to foster holistic and cooperative territory planning methods.
In Brazil, an example is the Citymetrics platform (LIMA, 2017), developed as a system that articulates performance evaluation metrics with algorithmic and parametric resources and functionalities. Its goal is to analyze and optimize different aspects related to urban sustainability. The parametric model was built from the perspective of measurable principles of TOD (Transit-Oriented Development), aiming to assist urban planning processes oriented by these principles.

4. Methodology

Thus, within the scope of the developed research, the construction of a parametric model was proposed to carry out the analysis and evaluation of the impacts of verticalization and urban intensification proposed in the Master Plan (BELO HORIZONTE, 2019) in the Regional Centrality Areas.

To achieve this, the model aimed to provide a three-dimensional visualization of the effects of the proposed occupation in the centrality areas and measure the performance of these areas from the perspective of metrics used to define sustainability criteria. To accomplish this, the research procedures were organized as follows:

1. Selection of the analysis area and collection of open data from selected layers in BHMaps;
2. Algorithmic modeling of occupation parameters for the Regional Centrality Areas in Rhinoceros software and Grasshopper plugin, with metadata transposed to the Urbano plugin;
3. Visualization of occupation parameters, analysis, and evaluation of environmental performance resulting from proposed intensification using the Ladybug add-on.

4.1. SELECTION OF THE ANALYSIS AREA AND DATA COLLECTION

The selected Centrality Area is located in the Pampulha Region, in front of the UFMG Campus, intersected by Antônio Carlos Avenue and near Pampulha Airport. This area has significant development potential due to its proximity to the university, making it a regional centrality that is expected to experience greater construction and population density in the near future. Furthermore, the proximity to the airport facilitates data collection through the EPW file, allowing for a more precise comparison between the current scenario and a future scenario predicted by the parameters of the new Master Plan.

First, open data was collected from the selected layers in BHMaps for the chosen regional centrality, and this data was transposed to the QGIS software. The collected data primarily included layers related to city blocks and buildings along with their respective heights, considering that the analysis would primarily focus on the impact of the buildings. To enhance the analysis, it was necessary to perform a geographic boundary selection in QGIS before exporting.

Subsequently, the data was imported into the Grasshopper parametric modeling plugin through the Urbano plugin's component, which allows the reading of shapefile metadata. Reading the metadata enabled the generation of the selected city block within a controlled environment, making it possible to analyze and assess the area's environmental performance and heat island formation using the Ladybug plugin. This plugin enables the reading of EPW climate files.

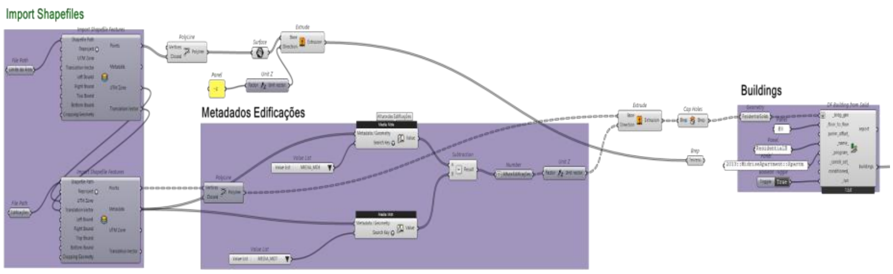


Figure 1. Capture Grasshopper, Import Shapefiles with Urban add-on, 2023. Author figure.

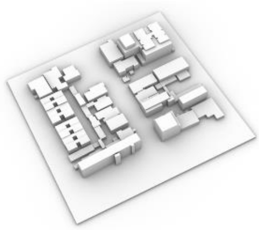
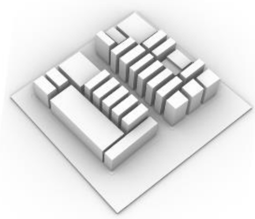
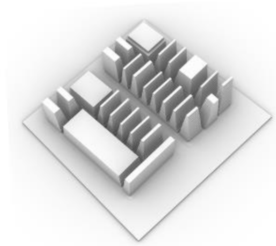
4.2. PARAMETRIC MODELING

Parametric modeling software enables the construction of interactive models that allow for a dynamic assessment of urban areas under study and proposed interventions. Beyond visualization possibilities, parametric and algorithmic models enable the creation of a metasystem capable of simulating complex dynamic processes, making it a fundamental tool for studying the complexity of the contemporary city and the overlapping diversity of parameters.

For the analysis of the selected area, the modeling process began by representing the city blocks in their current state. Subsequently, models were created for a potential future scenario resulting from the proposed

intensification outlined in the new master plan, as well as a scenario without the utilization of the H-rule according to the new master plan of Belo Horizonte. The H-rule involves a formula for calculating lateral and rear setbacks for buildings exceeding 12m in height, where the setback equals 2.3 + (H-12.0)/B (for regional centralities, B=8). One of the primary reasons for this rule's existence is due to the Sky View Factor (SVF) between buildings and on streets, given that very tall buildings tend to impact it. Thus, using the Ladybug add-on again, within a controlled environment, the plugin can simulate scenarios using temperature and relative humidity information from the EPW climate file, generating comparative graphs that reveal potential climate changes resulting from alterations in the urban setting.
Additionally, the Ladybug plugin also facilitates Sky View Factor analysis. Using a three-dimensional model, the component generates visual graphs enabling the analysis and comparison of various scenarios. In this case, three different scenarios were analyzed (TABLE 1):

TABLE 1. *Different city modeling scenarios, 2023.*

Current scenario of regional centrality	Possible scenario with maximum CA (5.0) and the H rule	Possible scenario with maximum CA (5.0) without H rule using 2.3 m distance.
		

5. Results

The results obtained through the environmental analysis using the Ladybug add-on demonstrated that with the intensification of buildings, the climate of the region would indeed undergo temperature changes, leading to heat islands. In the case of the H-rule, it is possible to identify, through color-coded graphs analysis, a plausible justification, as the rule achieves one of its objectives by not negatively impacting the Sky View Factor (SVF), unlike the scenario where the rule is not applied. As a result, we can observe that the parameters of the new master plan have both positive and negative aspects regarding sustainability.

5.1. CLIMATE ANALYSIS

For the climate analysis, we conducted a comparison between the impacts of the existing buildings on the region's climate and the potential impacts of a future scenario with buildings at their maximum plot ratio (CA) using the EPW file extracted by the Ladybug add-on. This process generated two comparative graphs, one for normal temperature and altered temperature, and another for normal relative humidity and altered relative humidity, for both scenarios over a one-year interval.

Based on these analyses generated by the Ladybug plugin, it became evident that there is an increase of at least 1°C in temperature for a significant part of the year, and a decrease in relative humidity in a potential future scenario under the influence of the new master plan. Consequently, it can be concluded that intensification does not contribute to environmental sustainability and aids in the formation of heat islands.

Figure 2. *Graphics of simulations of temperature and relative air humidity, 2023. Author figure.*

5.2. SKY VIEW FACTOR ANALYSIS

The Sky View Factor (SVF) analysis refers to an evaluation aiming to determine the amount of visible sky from a given location. It is commonly used in studies related to urban lighting, the impact of light pollution, and the assessment of night sky quality. A high percentage of SVF indicates good visibility of the night sky, while a low percentage suggests less visible sky.

The SVF is associated with various urban environmental processes, as it is a primary cause of heat island formation. This occurs because the cooling of the earth's surface is proportional to the visible sky area. Thus, the SVF percentage represents the fraction of available sky for heat exchange (SOUZA, 2010).

To analyze the sky view factor using the Ladybug add-on, it was first necessary to model the buildings in the scenarios under analysis: the current scenario, a potential future scenario with the H-rule, and a possible future scenario without the H-rule using a setback of 2.3m. Once the building geometries were modeled and imported, the plugin generated color-coded graphs that visualized the SVF percentages and the impacts caused by building heights. In these graphs, the color pink represents the lowest percentage, green signifies a medium percentage, and blue indicates the highest percentage.

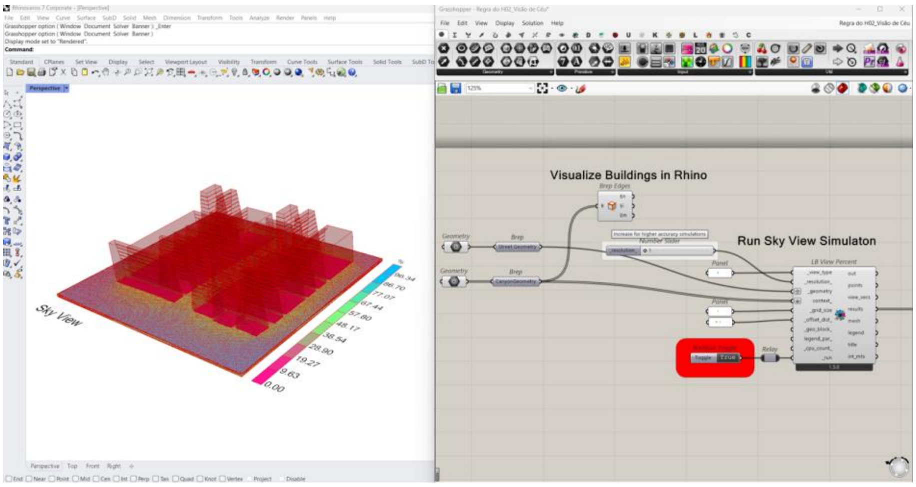


Figure 3. Capture of Sky View Simulation in Grasshopper with Ladybug add-on, 2023. Author figure.

With this, from the analysis of the sky view factor in three different scenarios, it was possible to observe that the increase in the coefficient significantly affects visibility, especially on the streets.

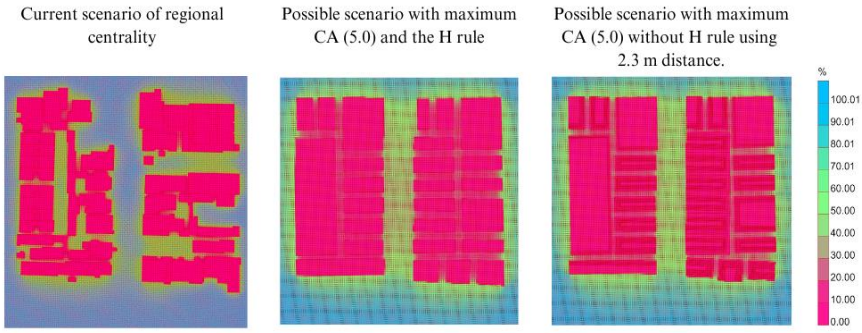


Figure 4. *Sky View Simulation with Ladybug, 2023. Author figure.*

5. Results

Contemporary cartography produced through digital mapping can be considered an infrastructure of public administration, as it provides a system for regulating space on a large scale. However, it can also open possibilities for data interpretation and visualization of intentions for urban planning. According to Picon (2015), the smart city is both an ideal and a process; this dual aspect allows this concept to escape mere urban utopias that are often laden with ambiguity. As a process, there are challenges that are simultaneously technological, environmental, social, and cultural, requiring dialogical approaches.

In this way, the availability of open data and the possibilities brought by emerging digital tools for the construction of performative parametric models can serve as devices to pragmatically test the relationship between urban parameters established by law and their contribution to sustainable urban development.

The tools used for urban performance analysis have the potential to predict possible climate changes resulting from changes in the urban scenario. The incorporation of these tools into urban planning could be crucial in avoiding future environmental damage. As demonstrated in the results of the analyses, the increase in the plot ratio can lead to changes in temperature and relative humidity, confirming the hypothesis that the increase in the coefficient does not contribute to environmental sustainability.

Furthermore, the results related to the sky view factor demonstrate that the H-rule does not necessarily contribute significantly to the visible sky area when buildings are at their maximum potential. Therefore, it can be concluded that the increase in the plot ratio is the factor that most negatively influences both environmental sustainability and the sky view factor.

Due to the high degree of flexibility and adaptability of the parametric model, we believe that the study can also serve for future research and complementary investigations, offering a tool for simulation and performance analysis not only of the relationship between morphological and environmental aspects but also of the impacts of socioeconomic dynamics resulting from urban intensification, converting the range of produced data into value of space use.
This research is expected to contribute to identifying challenges, strategies, and planning and urban design guidelines for Regional Centrality areas, as well as to cooperate in aligning urbanization processes with the principles of the compact city and environmental sustainability objectives. The hope is to contribute to more dynamic, participatory, and responsive processes, aiming for a more resilient and sustainable future for our cities.

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REINTERPRETING THE COURTYARD IN MODERN INDIAN ARCHITECTURE

A computational study on configurations

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Abstract. India is a land of significantly varying cultures, climates, and hence, a myriad of architectural styles and elements. Courtyard, one such element, had emerged as a result of multiple factors including not only climate and its context but the community and its culture as well. It is true reflection of the diversity that the country showcases. From the Havelis in Rajasthan and Gujarat to the Wadas in Maharashtra, it has always been an integral part of Indian architecture and its heritage. However, despite being such deeply rooted in the country's heritage, it has started to go missing in modern construction. Various changes in social, cultural, and climatic patterns have made courtyards either an element of luxury or a lost element of the past. What exists today is a vague notion of this element, whose origin is muddled, and the science behind it is lost. One needs to understand that leaving an empty space or a cut-out is neither the true identity nor the authentic form of a courtyard. This configuration depends on a plethora of factors, one of which is Enclosure, governed by width, length, and height. Configurations formed with varied enclosed proportions not only have a psychological influence on the user owing to volume change but also affect air circulation and temperature change. However, the modern application of courtyards is often theoretically examined, resulting in a lack of practical application of its methodologies and design techniques. Hence, different spatial possibilities create an opportunity to use computational methods such as modeling and simulation techniques to form cases of varying degrees and forms of enclosures. It enables the research to reinterpret courtyards in today's modern context using computer-aided design for a more data-driven exploration for higher human well-being in designed spaces, optimized microclimate, and a more sustainable building. Thus, the paper aims to understand the age-old concept of the courtyard through a scientific lens with the help of modern computational techniques. It will evaluate different configurations formed through simulations graphically. Through the case of Bengaluru, Karnataka, a modern city that experiences a temperate climate in India, the paper will showcase how changing enclosures and various positions of openings can incorporate the true essence of a courtyard in today's modern architecture. Further, a similar study of different climatic conditions can bring back the lost heritage to the country in its truest form through a futuristic design process that is not only data-driven but also more human and community-centric.

Keywords: *Computational Study, Courtyard, Human-centric Design, Heritage*

ملخص. الهند هي أرض الثقافات والمناخات المتنوعة بشكل كبير، وبالتالي، عدد لا يحصى من الأساليب والعناصر المعمارية. وقد ظهر الفناء، أحد هذه العناصر، نتيجة لعوامل متعددة، ليس فقط المناخ وسياقه ولكن المجتمع وثقافته أيضًا. إنه انعكاس حقيقي للتنوع الذي تعرضه البلاد. من هافيلي في راجاستان وجوجارات إلى واداس في ماهاراشترا، كانت دائمًا جزءًا لا يتجزأ من العمارة الهندية وتراثها. ومع ذلك، على الرغم من كونها متجذرة في تراث البلاد، إلا أنها بدأت تختفي في البناء الحديث. أدت التغيرات المختلفة في الأنماط الاجتماعية والثقافية والمناخية إلى جعل الساحات إما عنصرًا من عناصر الرفاهية أو عنصرًا مفقودًا من الماضي. وما يوجد اليوم هو فكرة غامضة عن هذا العنصر، وأصله مشوش، والعلم الذي يقف وراءه مفقود. يجب على المرء أن يفهم أن ترك مساحة فارغة أو فتحة لا يمثل الهوية الحقيقية ولا الشكل الأصيل للفناء. يعتمد هذا التكوين على عدد كبير من العوامل، أحدها هو العلبة، التي يحكمها العرض والطول والارتفاع. التكوينات التي تم تشكيلها بنسب مغلقة متنوعة ليس لها تأثير نفسي على المستخدم بسبب تغير الحجم فحسب، بل تؤثر أيضًا على دوران الهواء وتغير درجة الحرارة. ومع ذلك، غالبًا ما يتم فحص التطبيق الحديث للفناء من الناحية النظرية، مما يؤدي إلى نقص التطبيق العملي لمنهجياته وتقنيات التصميم. ومن ثم، فإن الاحتمالات المكانية المختلفة تخلق فرصة لاستخدام الأساليب الحسابية مثل تقنيات النمذجة والمحاكاة لتشكيل حالات بدرجات متفاوتة وأشكال من العبوات. إنه يمكّن البحث من إعادة تفسير الأفنية في السياق الحديث اليوم باستخدام التصميم بمساعدة الكمبيوتر لاستكشاف أكثر اعتمادًا على البيانات لتحقيق رفاهية أعلى للإنسان في المساحات المصممة، والمناخ المحلي الأمثل، وبناء أكثر استدامة. ومن ثم، تهدف الورقة إلى فهم المفهوم القديم للفناء من خلال عدسة علمية بمساعدة التقنيات الحسابية الحديثة. سيتم تقييم التكوينات المختلفة التي تم تشكيلها من خلال عمليات المحاكاة بيانياً. من خلال حالة بنغالورو، كارناتاكا، وهي مدينة حديثة تعاني من مناخ معتدل في الهند، ستعرض الورقة كيف يمكن للمحميات المتغيرة والمواضع المختلفة للفتحات أن تدمج الجوهر الحقيقي للفناء في الهندسة المعمارية الحديثة اليوم. علاوة على ذلك، يمكن لدراسة مماثلة للظروف المناخية المختلفة أن تعيد التراث المفقود إلى البلاد في أصدق صوره من خلال عملية تصميم مستقبلية لا تعتمد على البيانات فحسب، بل تركز أيضًا على الإنسان والمجتمع.

الكلمات المفتاحية: *دراسة حوسبية، الفناء، التصميم المرتكز على الإنسان، التراث.*

1. Introduction

The ongoing globalization has started causing a gradual dissolution of political, economic, and cultural barriers. While it undoubtedly brings advantages, ranging from economic expansion to improved quality of life, it has also spread and diluted distinct local cultural characteristics, particularly in the field of architecture. Irrespective of local differences, cultural uniqueness and varied climatic zones, modern architecture has begun to lose the identity of its origins (Rashid & Ara, 2015). Though it is quite difficult to integrate the true traditional elements of housing in contemporary context, understanding their logics from their origins might help to reinterpret them (Gupta and Joshi, 2021). A courtyard is one such element that has its roots in the cultural heritage of a traditional house but has lost its importance in the sands of time. Though we can still see instances of courtyards in modern houses, they are majorly done for aesthetic purposes (Soflaei et al., 2020: Gupta and Joshi, 2021).

A courtyard is a place that can be easily defined as a part of a home that is completely or partially enclosed by fortifications or man-made buildings (Rapoport, 1998; Muhaisen and Gadi, 2006; Mai and Shamsuddin, 2012; Berkovic and Bitan, 2012). They have existed from prehistoric times and even though today we know its cultural importance, while lacking an understanding based more on a quantitative assessment.

This research aims to address this knowledge gap by understanding the courtyards with respect to their thermal quality and interior spaces. This, in turn, has a significant impact on the social and cultural activities that traditionally take place in these courtyards. Studying the courtyards through this lens would give designers a better understanding to include the courtyards in their designs, while creating innovative new spaces for the traditional cultural activities, without compromising on the quality of space itself.

As an element to the buildings, courtyards help in getting rid of the accumulated heat gain in the building's-built structure. By facilitating improved and efficient natural ventilation, it replaces the trapped hot air with cool air due to wind pressure variations, hence, cooling down the whole building (Leila Moosavi, 2014). If it is designed properly according to the building, studies have confirmed experimentally that it can provide a better thermal performance result than any other building patterns used in today's architectural practices, (Cho S, 2013; Nada Al-Masri, 2012).

In a courtyard, the openings with respect to its total width, area and position contribute significantly to the view of the wind and its character in the space. Apart from only its openings, the geometric properties of courtyards, including the width, length, height, and periphery along with the area and orientation, also affects the shading and ventilation of the spaces (Omar Al-Hafith, 2019). However, there has been only limited research work on such impacts on ventilation and thermal quality of courtyards.

The study, for the quality of research, will primarily focus on designing courtyards for a temperate climatic zone. Taking into account all pertinent aspects from their geometry (ratios like width/length (W/L), width/height

(W/H), periphery/height (P/H), area and orientation) to the area of openings and their positioning (Ahmed Muhaisen, 2006), the courtyards will be studied graphically to understand the thermally comfortable spaces within an enclosed space. In practice often these factors are either lost or not considered in a design, resulting in unexpected wind flow or thermal quality, which might cause discomfort to the occupants in their daily life.

2. Background

2.1. CULTURAL IMPORTANCE OF COURTYARDS

Houses with courtyards have existed for thousands of years since the Neolithic settlements (Sthapak and Bandyopadhyay, 2014), and overtime have even generated cross-cultural validity all over the world. While their initial emergence can be attributed to climatic and thermal necessities, their widespread embrace is influenced by diverse factors such as religion, social norms, aesthetic preferences, leisure activities, cultural identity, status symbolism, and defensive considerations, which can vary by location. Examples range from the Nalukettu style in Kerala, the Havelis of Rajasthan, Wada homes in Gujarat, Pols in Ahmedabad, traditional houses in Goa, to the Chettinad houses of Tamil Nadu. (Vedhajanani and Amirtham, 2023).

These structures may be found in a number of different contexts, including a hallway or corridor, as well as a balcony or porch. It is a multifunctional outdoor area contained within a building that serves as an extension for internal activities, a vital venue for social gatherings/interactions, and a spot for a private space (Bretonne, 1979; Tablada et al., 2005; Salama, 2006). Further, these spaces play an active role in providing access to ample natural lighting as well as easy ventilation for all indoor spaces associated with them, (Soflaei, 2017). This results in an interaction of indoor spaces with controlled outdoor conditions, throughout the courtyard spaces included in the building.

Despite these positives, the courtyard is losing its significance in modern-day houses (Vedhajanani and Amirtham, 2023). This can be attributed to a number of factors such as growing population and rapid urbanization which puts a lot pressure on land resources in urban areas, further complicating the issue some other factors like stringent byelaws, Floor Area Ratio (FAR) calculation, As a result, the actual essence of courtyards getting lost due to the current design and construction practices (Gupta and Joshi, 2021).

2.2 CURRENT STUDIES

Previous research has shown that, as a climate-responsive design (Singh et al., 2009; Muhaisen and Gadi, 2006), the courtyard can affect the microclimate of the space by creating a regulating effect under specific weather conditions (Forouzandeh, 2017). This phenomenon is influenced by various factors, like ratios of width/length (W/L), width/height (W/H), periphery/height (P/H), area and orientation of the openings and their positions (Muhaisen, 2006), the materiality of the wall and floors enclosing the courtyard (Soflaei et al., 2020). These variables collectively contribute to potentially unforeseen variations in thermal comfort for courtyard users, largely contingent upon the specific design choices made.

Further, even though thermal comfort can be achieved by deploying additional strategies in courtyards, mechanical or passive, the design of the courtyard itself can be the best solution for thermal comfort. Increasing natural ventilation helps get rid of this accumulated heat gain in the buildings'-built structure as it replaces the trapped hot air with cool air due to wind pressure variation, hence cooling down the whole building (Moosavi,2014). Area, positions, and total width of openings are the main variables that highly influence the character of wind, both quantitatively and qualitatively, in the space interior of courtyards (Lawson, 1980; Yaza, 2018).

Occupant discomfort varies based on wind exposure, enclosure level, and courtyard wind conditions. If designed properly with all considerations, the courtyards can provide better thermal performance than any other building patterns used in today's architectural practices (Cho S, 2013; Masri, 2012). These elements contribute to the formation of a distinct microclimate within the confines of the courtyard. Furthermore, within this space, smaller alcoves are formed, each characterized by unique patterns of airflow and temperature. Ultimately, these variations culminate in the development of thermally optimized zones tailored for specific activities.

3. Methodology

This research aims to support better design of passive courtyard houses in the temperate climatic zone of India, by geo-locating the simulations to the city of Bangalore, in the southern portion of India. It experiences the highest temperature of 39.2 degree Celsius with an average rainfall of 970mm a year.

Figure 1. The research methodology adopted for the study (Author, 2023)

The study approach of this research is based on primary findings with an extensive literature review was conducted through existing literature to achieve the required parameters. followed by extracting the information based on simulation-based models constructed in Rhino/Grasshopper with the help of environmental-based plugins Ladybug, butterfly, and Honeybee. A widely acceptable tool for the accuracy in thermal results (Cabrza et al, 2022), while wind movement butterfly plugin has shown the best results among the 3 software namely Autodesk CFD, Butterfly, and GH_Wind (Hu et al., 2022).

In particular, a parametric study 60 configuration of courtyards was done using the Rhino/Grasshopper software with plugins like Ladybug, Honeybee, and Butterfly.

Where grasshopper is an interface to provide instantaneous feedback on the design-based Ladybug which imports standard EnergyPlus Weather Files and allows them to provide interactive graphics 137 to enhance a comprehensive decision-making process, while Honeybee gives the ability to work with 138 validated energy and daylighting engines such as EnergyPlus, Radiance, and Daysim with butterfly a Grasshopper plugin and object-oriented python library that creates and runs computational fluid dynamics (CFD) simulations using OpenFOAM.

These instances, simulated and analyzed visually, were assessed in terms of their thermal attributes and wind velocities. A set of cases of different courtyard geometries were developed, each with unique thermal configurations and which holds true for buildings with minimum height of 4.5 meters to maximum 18 meters. To identify the better-performing ratio, sizes and location of openings for the courtyards. Further, table 1 shows the assumed values for the simulations conducted.

TABLE 1. Values assumed for the simulations (Author, 2023).

Parameters	Assigned Values	Based On
Date	2 May 2020	A random day in the hottest week of the year 2020.
Openings	2mX3m (fixed)	Assumed
Shading System	Not Assigned	No particular good result by simulation software for the same
Solar Distribution	Full Interior and Exterior (fixed)	Honeybee
Windspeed	1.5 m/sec outdoor (speed of wind recorded on for the day of simulation)	Based on EPW file data of the hottest day in Bengaluru
Temperature	37.8	Based on EPW file data of the hottest day in Bengaluru
Direct horizontal radiation		Based on EPW file data of the hottest day in Bengaluru
Diffuse horizontal radiation		Based on EPW file data of the hottest day in Bengaluru
Relative humidity		Based on EPW file data of the hottest day in Bengaluru

4. Selection of Parameters

4.1 IDENTIFICATION OF VARIOUS RATIOS FOR COURTYARDS AND OPENINGS

Physical boundaries define a space's three-dimensional volume, conveyed as ratios to indicate proportion. Altering these boundaries creates new spaces with fresh relationships to associated spaces. The spatial proportion thus achieved as a result in two kind of relationships; one of ratio between the building’s height and width, and the length and width (Booth N., 2011).

Both types of spatial proportions are merged with one another resulting in compound space’s proportions of courtyards, which should be assessed as a whole, and not individual.

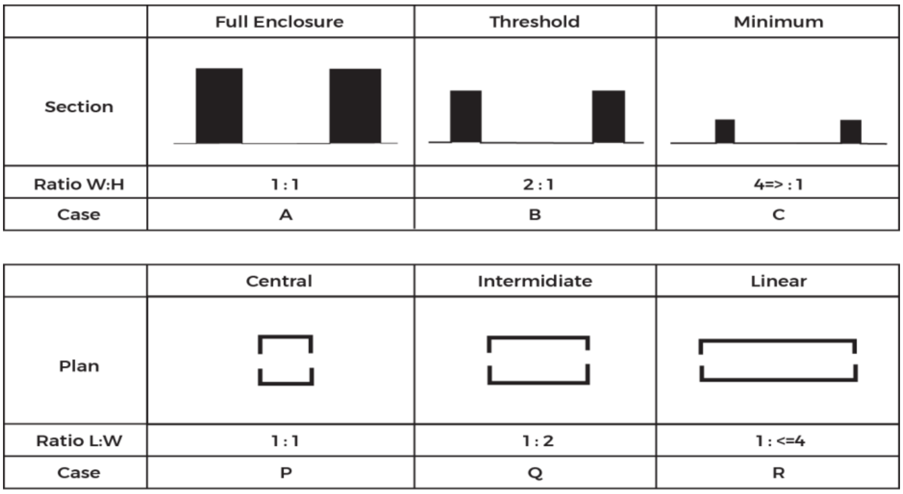


Figure 2 Types of enclosures based on Booths and Robinette classification. (Gabr, 2019)

4.2 IDENTIFYING THE BASIC UNIT SIZE OF THE COURTYARD

To keep the relevance of the study. The research has used 9 different configurations of varied proportions considering the building height of floor-to-floor height of 3.6 m and a parapet height of 0.9 m for keeping it relevant to human proportions according to the standards followed in India, i.e., National Building Codes (NBC) 2016. Thus, the length, width, and height taken is 4.5X4.5X4.5 meters.

4.3 FORMATION OF VARIOUS CASES

In alignment with Robinette’s degree of enclosure and Booth’s form of enclosure the matrix has been formed with the degree of enclosure in row form starting with full enclosure i.e., width-to-height ratio of 1:1 carried by case B (threshold) ending with case C (minimum enclosure). The form in the enclosure is marked in columns starting with Central marked as case P with Length to width ratio of 1:1 followed by case Q (intermediate) with length to width ratio of 1:2 further caring on case R (linear) with length to width ratio 1: =>4.

Thus, forming various cases in the matrix like case AP with ratio Length: Width: Height equals 1:1:1 dimension of 4.5m each. Similarly following cases BP, and CP to case CR formed 9 such permutations of the courtyard for the simulation. Which are them multiplied with basic unit sizes to attain the simulation model.

TABLE 2. Matrix of various cases of courtyards based on proportions. (Author)

S.No.	Ratio Case	Full Enclosure (A) W:H :: 1 : 1			Threshold (B) W:H :: 2 : 1			Minimum (C) W:H :: 4=> : 1			
		L	W	H	L	W	H	L	W	H	
1.	Central (P) L:W :: 1 : 1	1	1	1	2	2	1	4	4	1	Ratio
		4.5	4.5	4.5	9	9	4.5	18	18	4.5	Measuments
		AP			BP			CP			Cases
2.	Intermidiate (Q) L:W :: 1 : 2	1	2	2	1	2	1	2	4	1	Ratio
		4.5	9	9	4.5	9	4.5	9	18	4.5	Measuments
		AQ			BQ			CQ			Cases
3.	Linear (R) L:W :: 1 : =<4	1	4	4	1	4	2	1	4	1	Ratio
		4.5	18	18	4.5	18	9	4.5	18	4.5	Measuments
		AR			BR			CR			Cases

4.4 AREA AND ORIENTATIONS OF COURTYARDS

The area and orientation of the opening play a vital role in deciding the rate and level of airflow in the courtyard. Thus, keeping in mind the direction of airflow, i.e., from the west side there are 9 different cases formed for the simulation of 1 typology of the courtyard from different proportions of the courtyard example AP will have 9 different cases within itself ranging from case 1 to case 9.

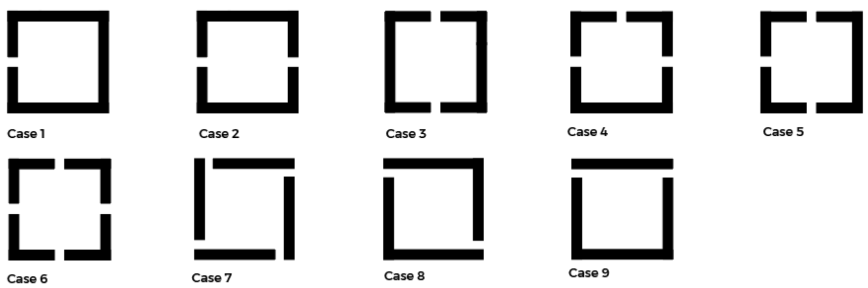


Figure 3. Matrix of cases of openings to the courtyards (Author)

5. Case Obtained

From the above-mentioned parameters a total of 60 different cases were achieved out of which the cases consisting of only narrow pathway in the name of courtyard are not being studied. These cases were further analyzed using the same legend for temperature and wind flow.

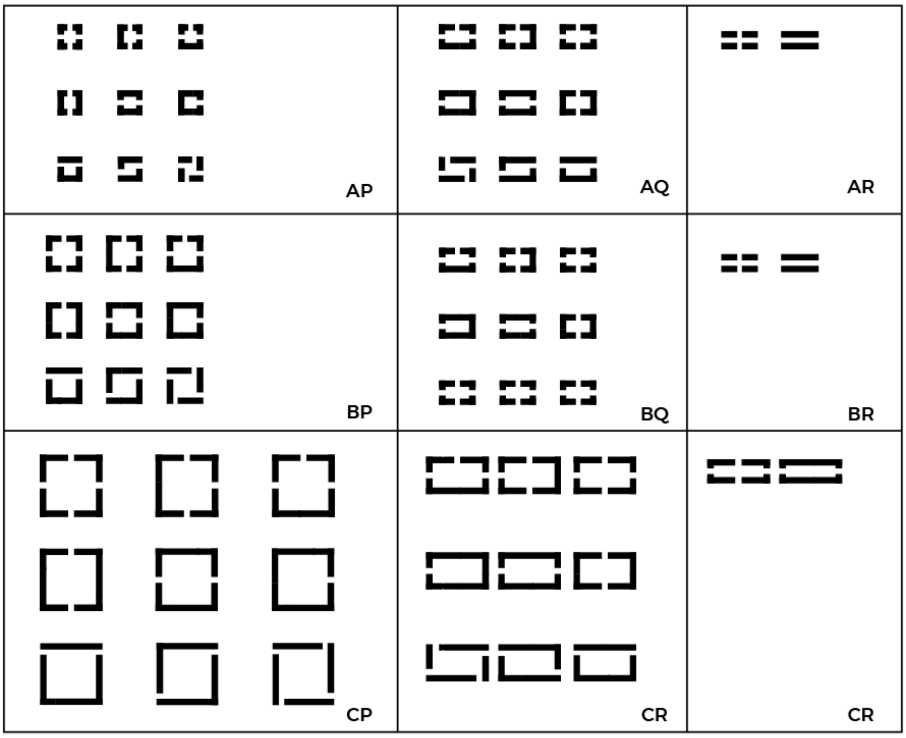


Figure 5. Matrix of cases to be studied through the simulation (Author)

5.1 LEGEND

For the forthcoming results, the following legends has been used to analyze the windspeed and temperature in degrees Celsius, as shown in figure 4.

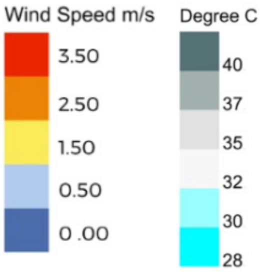


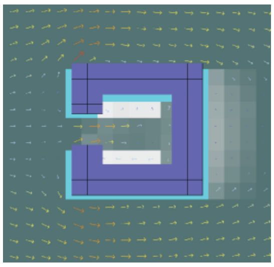
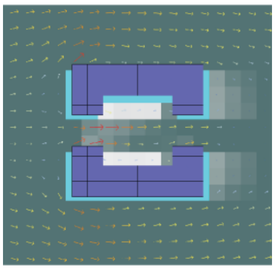
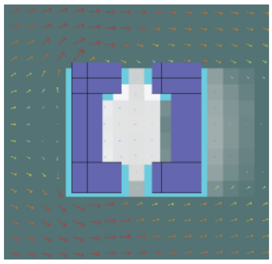
Figure 4. Legends used for all the simulations (Author)

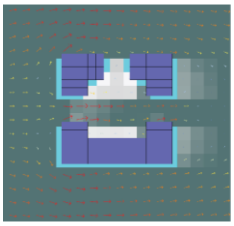
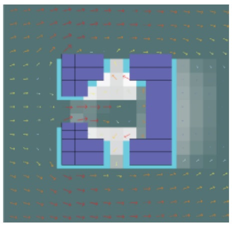
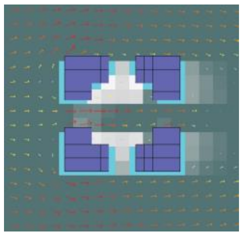
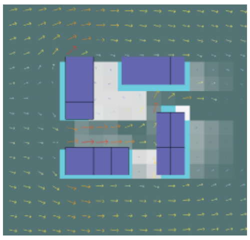
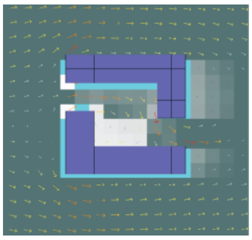
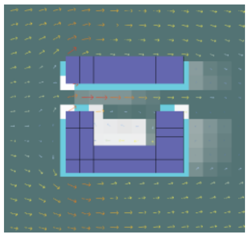
6. Results

6.1 CASE AP

The case AP has a ratio of 1:1:1 for the length, width and height. It can be observed that this instance provides for courtyards with 39-45 percent of its land area being shaded. With case, AP 3 has a maximum shaded area of 78 percent. Further, on observing the wind movement pattern a light to gentle breeze can be felt in all the cases where opening and cross ventilation is present in the direction of the natural wind movement. in case AP 8 light to Gentle breeze can be felt in 64.3 percent of the courtyard making it more comfortable in comparison to the cases AP 2, AP 4, AP5, AP 6, AP 7, AP 8 which are also cross-ventilating the area. Making cases AP 3 as very suitable for relaxing while case AP 8 can be considered best in regard to other wind and shade.

TABLE 3. Simulation for case AP

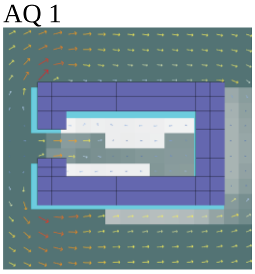
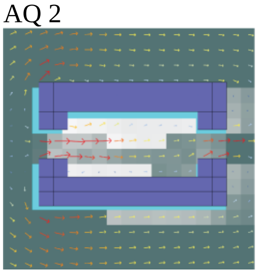
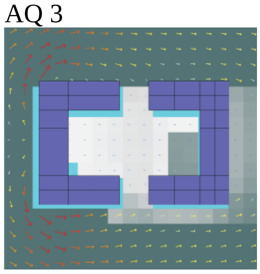
AP 1 	AP 2 	AP 3 
AP 4	AP 5	AP 6

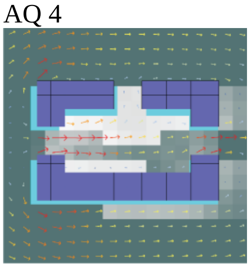
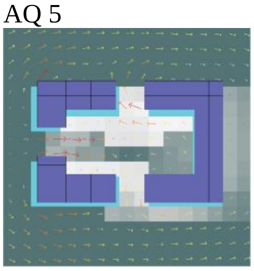
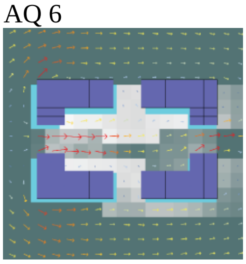
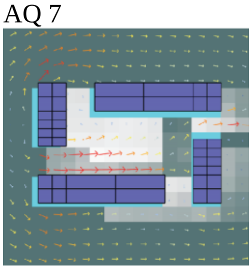
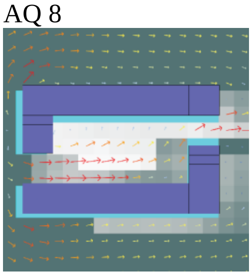
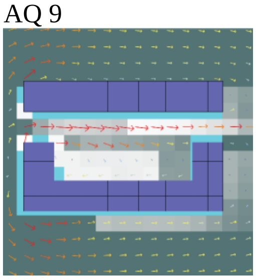
		
AP 7 	AP 8 	AP 9 

6.2 CASE AQ

The case AQ has the ratio of 1:2:2 for the length, width and height. It can be observed that this instance provides for a better typology for cases of shaded courtyards with 58-65 percent of its land area being shaded. With case AQ 3 having maximum shaded area of 80-85 percent of its land shaded. Further, on observing the wind movement pattern a light to gentle breeze can be felt in all the cases where opening and cross ventilation is present in the direction of the natural wind movement. On further observation it can be said that in the case of linear alignment the velocity of wind reduces in the central region. While in cases AQ 7, AQ 8, AQ 9 a better wind movement can be observed with 68-72 percent of its area under influence of light to gentle wind.

TABLE 4. Simulation for case AQ

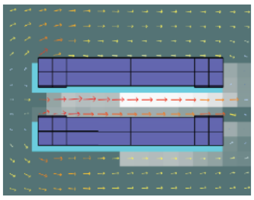
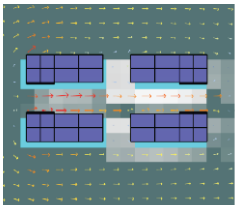
AQ 1 	AQ 2 	AQ 3 

AQ 4 	AQ 5 	AQ 6 
AQ 7 	AQ 8 	AQ 9 

6.3 CASE AR

The case AR has the ratio of 1:4:4 for the length, width and height. According to the Beaufort scale only light air can be felt in all the cases of AR and only a temperature drops of 5 degrees Celsius can be felt in 45-50 percent of its area.

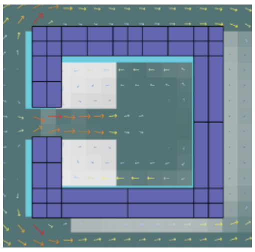
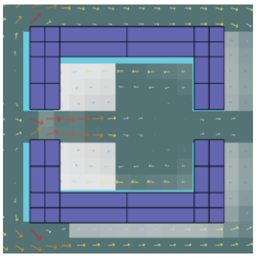
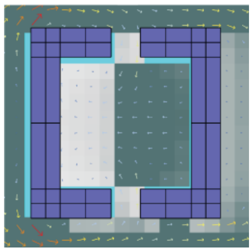
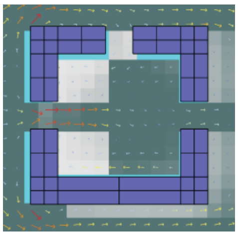
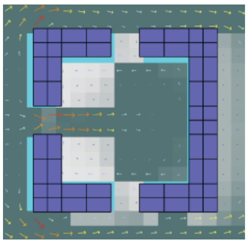
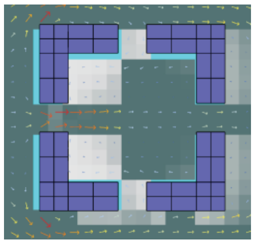
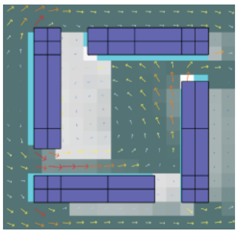
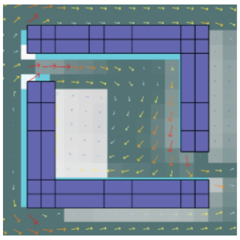
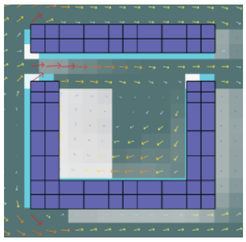
TABLE 5. Simulation for case AR

AR 1 	AR 2 

6.4 CASE BP

In case BP, with a 2:2:1 ratio for length, width, and height, courtyards cover 29-35% of the land area and can provide up to 40% shade in BP 3. Wind conditions range from calm to gentle breezes in all cases. Notably, linear alignment reduces wind velocity in the central region. Courtyards with a single opening offer better air circulation (34.5%) compared to 9.8% for BP 4, BP 5, and BP 6. The best air circulation (64-66%) is found in cases BP 7, BP 8, and BP 9, making courtyards with openings on opposite sides a preferable design choice.

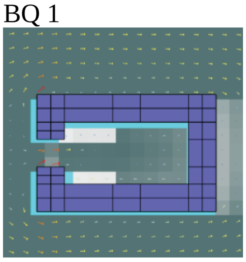
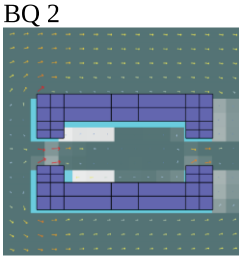
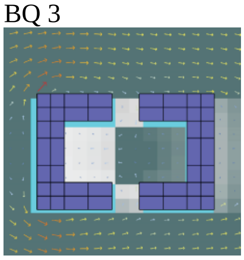
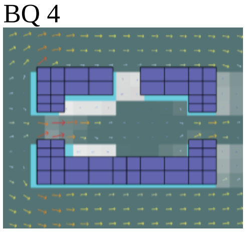
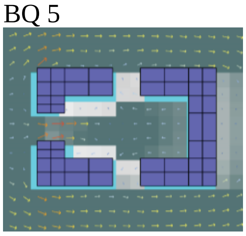
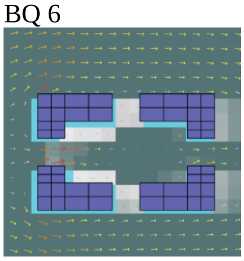
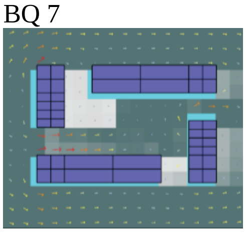
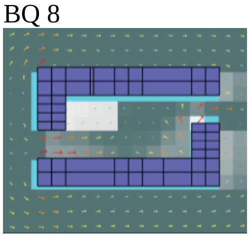
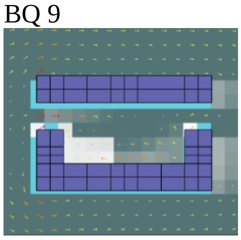
TABLE 6. Simulation for case BP

BP 1 	BP 2 	BP 3 
BP 4 	BP 5 	BP 6 
BP 7 	BP 8 	BP 9 

6.5 CASE BQ

The case BQ has a ratio of 1:2:1 for the length, width, and height. A poor performance in the case of both thermal comfort through shading and wind movement in the following cases. With maximum shading in the cases where the opening is at 90 degrees from the sun providing shade to 44 percent of its area only calm or light air can be felt in the cases thus making it uncomfortable for the user. While a light breeze can be felt in certain cases it only ranges from 18-22 percent making cases inefficient in terms of comfort.

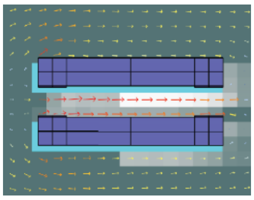
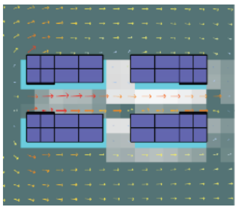
TABLE 7. Simulation for case BQ

BQ 1 	BQ 2 	BQ 3 
BQ 4 	BQ 5 	BQ 6 
BQ 7 	BQ 8 	BQ 9 

6.6 CASE BR

The case BR has a ratio of 2:4:1 for the length, width, and height. A good performance for the shading and air movement can be seen in both cases of BR with light to gentle breeze throughout the courtyard. And temperature reduction of 5-8 degrees Celsius throughout the courtyard. This makes the courtyard suitable for adoption in design.

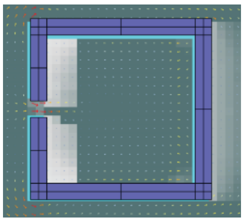
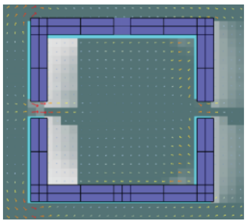
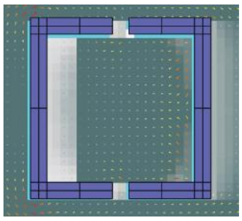
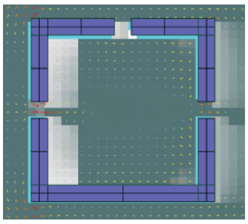
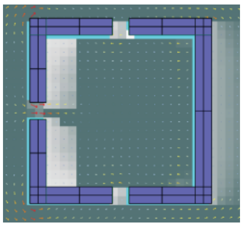
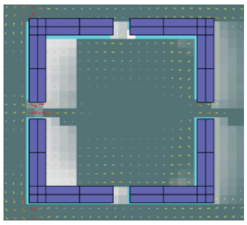
TABLE 8. Simulation for case BR

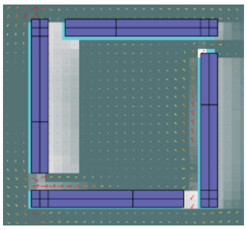
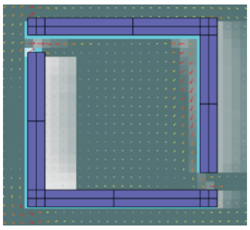
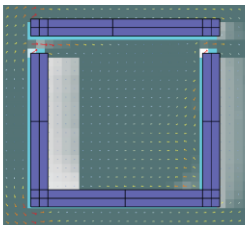
BR1 	BR 2 

6.7 CASE CP

In case CP, with a 4:4:1 ratio for length, width, and height, courtyards occupy 21-23% of its land area and experience varied wind conditions. Calm to gentle breezes prevail throughout the courtyard, while at the edges opposite to the wind direction, light to gentle breezes are observed. Among these, CP 3 has the highest wind movement, with 22.22% light air to light breeze.

TABLE 9. Simulation for case CP

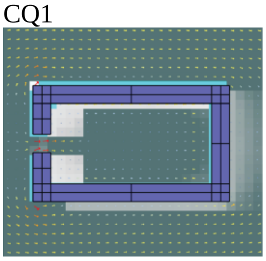
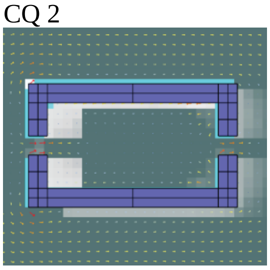
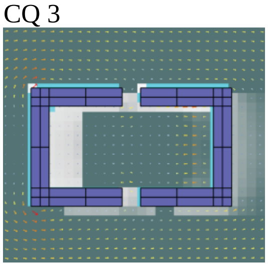
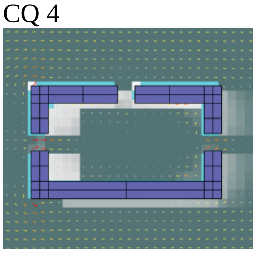
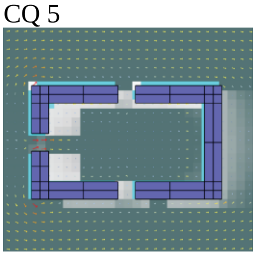
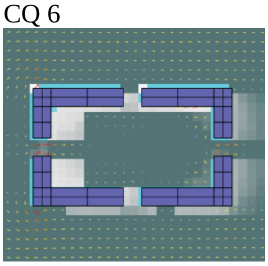
CP 1 	CP 2 	CP 3 
CP 4 	CP 5 	CP 6 
CP 7	CP 8	CP 9

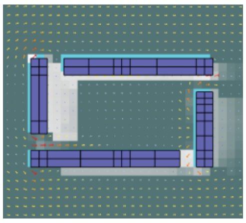
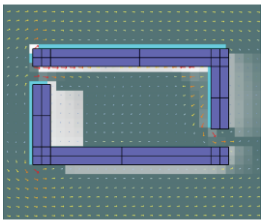
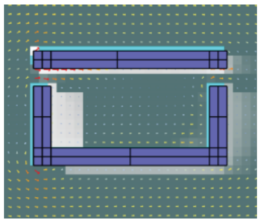
		

6.8 CASE CQ

The case CQ has a ratio of 2:4:1 for the length, width, and height. It is observed that this instance provides for courtyards with 21-23 percent of its land area being shaded. Further, on observing the wind movement pattern a calm to gentle breeze can be felt in all cases thus providing a varied sense of wind at different places in the courtyard. It is also found that at the edges of the courtyard on the opposite side of the wind direction light to gentle breeze can be found. Also, the case CQ 3 provides the maximum area with air movement i.e. 22.22 percent. Making these cases similar to that of cases CP.

TABLE 10. Simulation for case CQ

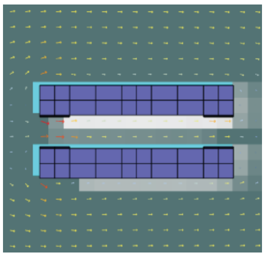
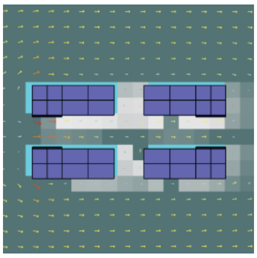
CQ1 	CQ 2 	CQ 3 
CQ 4 	CQ 5 	CQ 6 
CQ 7	CQ 8	CQ 9

6.9 CASE CR

The case CR has a ratio of 2:4:1 for the length, width, and height. A good performance for the shading and air movement can be seen in both cases of CR with light to gentle breeze throughout the courtyard. And temperature reduction of 5-8 degrees Celsius throughout the courtyard. This makes the cases suitable for design as well.

TABLE 11. Simulation for case CR

CR 1	CR 2
	

7. Discussion

Amongst the pool of 60 simulations created and examined based on wind movement and thermal performance. Throughout in the various cases of the courtyards a pronounced change in temperature and wind movement is present (table 3 to 11). Thus, various cases present under common points were analyzed ground based on table 2. Those are AP, BP and CP ground together under common height and varying area, cases AR, BR and CR common length and width with varying heights, Cases AP, BQ and CR with change in width of courtyard and Cases AP, AQ and AR with changing length of courtyard.

Thus, when moving from case the AP to case BP the substantial increase in amount 0-0.5 m/s to 2.5-3.5 m/s, while moving from BP to CP the air movement again down to 0-0.5 m/s for the majority part of courtyard, showing that ratio of case BP to be optimum for wind movement. In cases AR, BR and CR with decrease in height with constant length and width ratio the wind movement from 3.5m/sec> to 0-0.5 showing that linearly with increase in height of courtyard the wind speed increases. In cases AP, BQ and CR with variation in width of courtyard the natural ventilation is hampered showing that for equal length and breadth the natural ventilation works the best. While in cases AP, AQ and AR it can be seen with decrease in width and increase in height the thermal and wind performance has gotten better for the courtyards showing with increase in height and decrease in width the more area under courtyard get shaded and natural ventilation also gets prominent.

While looking for the cases of the openings under various cases only the cases AP, AQ, AR, BP and BR a good amount of natural ventilation can be found. For the case AP cases AP1, AP6, AP7 and AP8 (table3) have performed well while for the cases AQ (table 4) and BP (table 6) cases AQ2, AQ6 to AQ9 and BP7 to BP9 have performed well respectively in context of natural ventilation showing cross ventilation from the center, one side or at alternate side of the opposite wall works well for air circulation.

Thus, while comparing to the previous research done on the topic of courtyards. It is found that the result aligns as with decrease in width and increase in height of the courtyards the temperature inside the courtyard falls (Muhaisen, 2006; Soflaei et al.,2017; Aldawoud & Clark,2008) while comparing for the natural ventilation as previous research suggests that wide courtyards with cross ventilation have more active ventilation (Soflaei, Shokouhian, et al.2016; Mousli & Semprini, 2016) contradicts as on the basis of cases AP, AQ, AR, BP and BR.

8.Conclusion

To evaluate the thermal and natural ventilation performance of the courtyard ratios of length, width and height based on the types of enclosures were taken up with various positions of uniform perforations in these enclosures. Forming pool of 60 district cases based on National Building Codes, openings and enclosers. Then these cases were modelled, and computer simulations were run on them under temperate climatic conditions of Bengaluru. Concluding that with the decrease in the width and increase in the heights of the courtyards the thermal condition under the courtyards improves in temperate climatic zone. Further, with increase in area of courtyards from 1 to 4 time and then 4 till 16 time having constant height, first the natural ventilation increases then the natural ventilation decreases.

While with increase in the height the natural ventilation inside the courtyard increases. The best natural ventilation can be found in square courtyards while with reduction in its width at same height the natural ventilation becomes poor. While considering constant length with decrease in width and increase in height of courtyard the natural ventilation and thermal performance of courtyard gets better. Further it was found that the direction and location of opening shall also be looked upon based on ratio of courtyards as one-sided openings and alternate openings on opposite sides of courtyards perform well in rectangular courtyards while central opening on opposite courtyards only performs well in square courtyards. In regions characterized by temperate climates in India, scenarios akin to cases AQ and BR were found to provide optimal outcomes. Nonetheless, depending on the intended user activities and purposes, other cases from the resulting template could also be considered and used.

Further, additional correct findings require additional instances in the evaluation as well as field measurements to support the numerical model, which may be done in future study. The design recommendation for this investigation. The process may be generalized to different climates using the same manner.

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STATE-OF-THE-ART ON RESEARCH AND APPLICATIONS OF MACHINE LEARNING IN BUILDING ENERGY PERFORMANCE PREDICTION

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Abstract. The construction sector is responsible for 40% of the total energy consumption. The parameters that affect the energy performance of buildings include heating-cooling systems, ventilation systems, lighting, and the implementation of the Energy Performance of Buildings Directive (EPBD) by the European Union. Several regulations and certification systems like PassivHaus, LEED, BREEAM etc. have been developed to regulate this process. There is often a significant discrepancy between the estimated (calculated) energy performance of buildings and the actual energy usage after buildings are operational. This study reviews the efforts made within the context of machine learning to address this 'performance gap'. The systematic literature review focuses on machine learning-based approaches in the context of building energy performance. The areas of focus include reducing the gap between building energy performance predictions and the values obtained during the building's life cycle, and the dynamic updating of the building energy model based on data. The study highlights trends related to the use of machine learning in predicting building energy performance. These trends include the types of buildings considered, the algorithms used, the data utilized, and the targeted areas of energy performance. To conduct the study, a comprehensive literature review was performed using the PRISMA method, which yielded 325 relevant articles out of 3078 articles extracted from the Web of Science database. A bibliometric analysis was then carried out on these 325 articles. From the selected 325 articles, 30 high-impact articles were subjected to content analysis to evaluate potential gaps in the field.

Keywords: *Buildings Performance Prediction, Performance Gap, Prediction, Machine Learning*

ملخص. يعد قطاع البناء مسؤولا عن 40% من إجمالي استهلاك الطاقة. تشمل المعلمات التي تؤثر على أداء الطاقة في المباني أنظمة التدفئة والتبريد وأنظمة التهوية والإضاءة وتنفيذ توجيهات أداء الطاقة في المباني (EPBD) من قبل الاتحاد الأوروبي. وقد تم تطوير العديد من اللوائح وأنظمة إصدار الشهادات مثل PassivHaus وLEED وBREEAM وما إلى ذلك لتنظيم هذه العملية. غالبًا ما يكون هناك تناقض كبير بين أداء الطاقة المقدر (المحسوب) للمباني والاستخدام الفعلي للطاقة بعد تشغيل المباني. تستعرض هذه الدراسة الجهود المبذولة في سياق التعلم الآلي لمعالجة "فجوة الأداء" هذه. تركز المراجعة المنهجية للأدبيات على الأساليب القائمة على التعلم الآلي في سياق بناء أداء الطاقة. تشمل مجالات التركيز تقليل الفجوة بين تنبؤات أداء طاقة المبنى والقيم التي تم الحصول عليها خلال دورة حياة المبنى، والتحديث الديناميكي لنموذج طاقة المبنى بناءً على البيانات. تسلط الدراسة الضوء على الاتجاهات المتعلقة باستخدام التعلم الآلي في التنبؤ بأداء الطاقة في المباني. وتشمل هذه الاتجاهات أنواع المباني التي تم النظر فيها، والخوارزميات المستخدمة، والبيانات المستخدمة، والمجالات المستهدفة لأداء الطاقة. لإجراء الدراسة، تم إجراء مراجعة شاملة للأدبيات باستخدام طريقة PRISMA، والتي أسفرت عن 325 مقالة ذات صلة من أصل 3078 مقالة مستخرجة من قاعدة بيانات Web of Science. ثم تم إجراء تحليل ببليومتري لهذه المقالات البالغ عددها 325 مقالة. من بين 325 مقالة مختارة، تم إخضاع 30 مقالة عالية التأثير لتحليل المحتوى لتقييم الثغرات المحتملة في هذا المجال.

الكلمات المفتاحية: *تنبؤ أداء المبانى، فجوة الأداء، التنبؤ، التعلم الآلى.*

1. Introduction

In terms of prediction, modeling conditions exist that take into account uncertainties that are unknown during the design stage, such as the actual construction of a building, weather conditions, the behavior of individuals within the building, and HVAC control systems.

The detection and quantification of structural construction errors, as well as the identification of user behavior, require a complex sensor network. This situation often leads to insufficient data availability, necessitating approximate data and simulation for analysis (de Wilde, 2014).

Building modeling and energy performance prediction are areas of study that require interdisciplinary collaboration for further development (Foucquier et al., 2013). Optimizing building energy performance is influenced by all stages, from the design phase to the end of the building's lifecycle. Predicting building energy consumption is necessary for energy planning, management, and conservation. Estimating building energy consumption is important for making better decisions aimed at reducing energy consumption and carbon emissions (Foucquier et al., 2013).

The energy performance gap in buildings, achieving performance targets in energy-efficient buildings, and energy performance prediction for consumption forecasts in smart grids are important. The methods/models used for prediction are grouped into engineering models, Artificial Intelligence (AI)-based models, hybrid approaches, and data-driven models.

Contemporary buildings have become increasingly dynamic and intricate. They encompass conventional energy service systems, encompassing lighting, plug loads, HVAC (heating, ventilation, and air-conditioning), and service hot water. Moreover, these buildings incorporate on-site energy generation systems like solar photovoltaic (PV) panels, wind turbines, energy storage systems, and charging infrastructure for electric vehicles.

The optimal operation of these buildings, known as grid-interactive efficient buildings (GEBs), necessitates the achievement of energy efficiency, demand flexibility, and resilience. However, accomplishing these objectives has become more complex due to the integration of various systems, uncertainty regarding demand and supply, and the influence of energy or carbon signals from the energy grid. The prevailing methods of data analytics, modeling, or simulation are insufficient in addressing these evolving needs and challenges.

Under the scope of a literature review focused on machine learning, algorithms obtained in the field of energy performance prediction in buildings have been compiled. Artificial intelligence encompasses the integration of human behavior and intelligence into machines or systems, while machine learning enables the creation of analytical models that learn from data or past experiences through automation. Deep learning, on the other hand, involves multi-layered neural networks and computational processing (Esrafilian-Najafabadi & Haghighat, 2021).

Zhun et al. (2010) have identified seven factors that affect energy performance prediction in buildings. These factors include climate data, building characteristics (type, area, location), user density, building service systems and operations (heating, cooling, hot water), user behavior, social and economic factors, and indoor air quality (as a preferred factor) (Yu et al., 2010). Additionally, they have summarized the data related to buildings into three categories: climate data, building operational data, and building physical parameters.

In their study, Mohapatra et al. (2015) highlighted that Artificial Neural Networks (ANN) are preferred among other techniques due to their overall performance as an efficient and reliable prediction approach . Regression models were also identified as a long-term building energy prediction approach due to their simplicity in calculation strategies and ease of use. Support Vector Regression (SVR) algorithms are utilized not only as good classification tasks for prediction accuracy but also for building energy consumption analysis. Other algorithms, such as ensemble models, decision trees, Long Short-Term Memory (LSTM), and time series approaches, have been employed to construct energy consumption analyses. Survey results conducted in the same study showed that models demonstrating good performance in a short period are neural networks, support vector machines, decision trees, and K-means models. Deep learning models and optimization techniques were emphasized to outperform engineering methodologies in data-driven approaches for urban-scale energy consumption analysis.

The data on building performance tracked by modern measurement and monitoring systems, implemented with smart management systems, serves as a valuable database for energy prediction and improvement. Regression models are commonly used for total electrical load, HVAC systems, and reinforcement (Yildiz et al., 2017).

Building energy prediction models are crucial for energy management and improvement. Tanveer et al. (2018) have summarized the predicted energy areas into five categories, as indicated in the graph. More than 50% of the studies have focused on predicting the total building energy consumption (Figure 1).

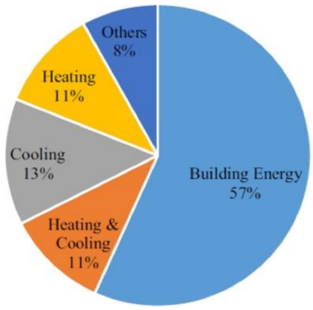

Figure 1. Building energy usage distribution (heating, cooling, ventilation, total building energy consumption, and other miscellaneous energy uses) (Ahmad et al., 2018)

Amasyali and El-Gohary (2018) provide a new modeling approach for building energy system studies using agent-based models. This approach allows for detailed modeling within each agent model and connects different agents that can easily implement different operational strategies. Agent-based models have been used for modeling and operation studies involving multiple buildings.

Akinosho et al. (2020) graphically illustrated the types of deep learning techniques used in the construction sector and their frequency of usage. Convolutional Neural Networks (CNN) were identified as the most commonly used algorithm.

From this context, this paper presents a systematic literature review focuses on machine learning-based approaches in the context of building energy performance.

2. Methodology

Bibliometric analysis is a quantitative research method used to study and evaluate scientific literature, typically academic publications such as journal articles, conference papers, books, and patents. It involves the application of statistical and mathematical techniques to analyze patterns, trends, and relationships within a specific set of documents or across a particular field of study.

In recent years, numerous detailed or simplified prediction approaches have been proposed and applied to various problems. In this study, the PRISMA bibliometric analysis method has been employed to focus on the utilization of machine learning in the field of energy performance in buildings.

To determine the proportion of these publications related to machine learning, keyword analysis has been conducted. The articles have been filtered separately for the most commonly used keywords: "machine learning, deep learning, artificial neural networks, data mining." As a result, it has been determined that out of the 758 articles, 298, 113, 273, and 74 articles are focused on machine learning, deep learning, artificial neural networks, and data mining, respectively. By eliminating duplicate and out-of-scope articles, a total of 325 publications were identified. For content analysis, a set of 30 publications was selected, consisting of the two most cited publications for each year from the 325 articles, along with the top 10 most cited publications from the remaining articles.

The objective of this study is to explore the utilization of machine learning for predicting building energy performance, employing VOSviewer, a bibliometric mapping program. Within the Web of Science (WOS) platform, a comprehensive total of 3078 articles have been identified in the field of energy performance prediction in buildings. (Figure 2).

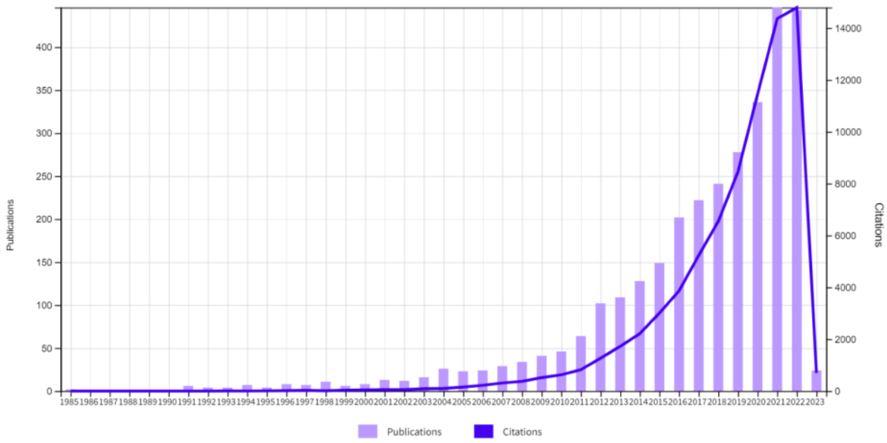

Figure 2. Literature search results

The study aimed to evaluate the research trends in the field of building energy performance prediction. Starting from the design stage and throughout buildings life cycle, energy consumption is crucial at every stage. It is important to predict and optimize energy consumption in advance for its improvement and enhancement.

3. Findings

According to the categorization system of the Web of Science (WOS), out of the 3078 articles used for analysis, 46 of them are in the field of Architecture, while 3042 are in the field of Construction and Building Technology (Table 1).

TABLE 1. Categories of the 3078 publications

Web of Science Categories	**Record Count**
Construction and Building Technology	3042
Architecture	46

The distribution of publications by countries is presented in Table 2. China has been the leading country in terms of the number of publications in the field. The journal "Energy and Buildings" has the highest number of publications (Table 3). "Building and Environment" and "Construction and Building Materials" journals rank second and third, respectively, in this ranking, as shown in Figure 3.

TABLE 2. Countries that have produced the most publications in this field

Countries	Record Count/%
China	992 / 32.229
USA	580 / 18.843
England	297 / 9.649
Canada	189 / 6.140
South Korea	173 / 5.621
Italy	122 / 3.964
France	114 / 3.704
Australia	106 / 3.444
Japan	103 / 3.346
Germany	90 / 2. 924

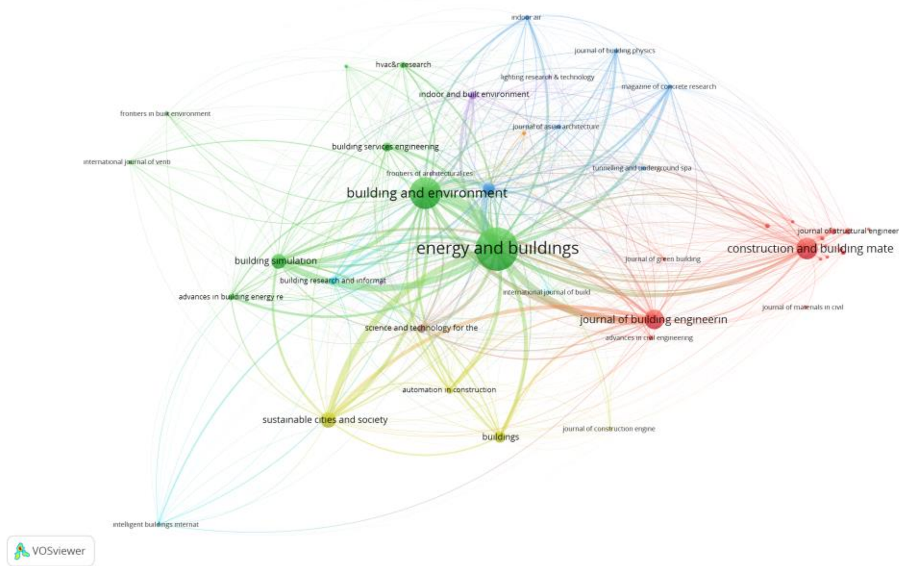

Figure 3. Journal publication frequencies and citation relationships.

Table 3 includes the top five authors with the highest number of publications in the field. The author ranked first is both the most prolific in terms of publications and the most cited. However, the author ranked fifth holds a stronger influence in the overall impact.

TABLE 3. Individuals with the highest number of publications in the field

Author	Documents	Citations	Total Link
Fariborz Haghighat	22	1157	13
Lin Borong	18	382	31
Wei Wang	18	337	13
William O’Brien	17	412	17
Zhang Lin	17	397	27

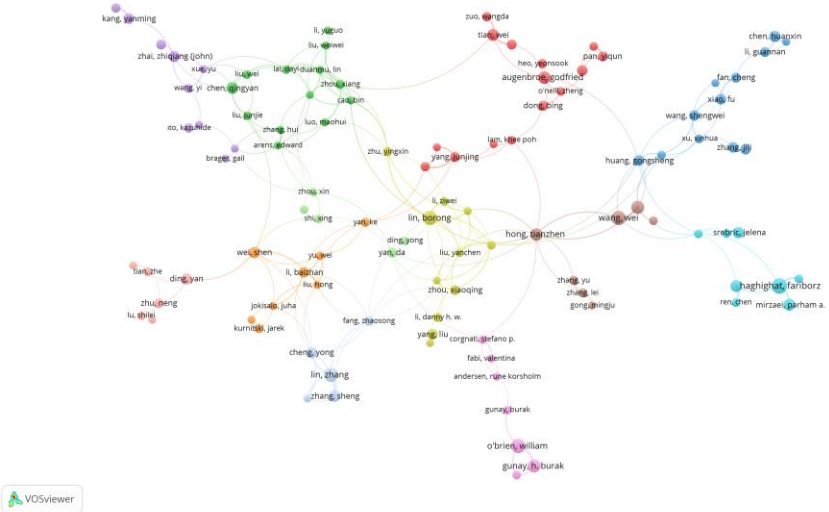

Figure 6. VOSviewer authorship collaboration analysis

The studies that became prominent between 2016 and 2018 show a noticeable shift towards machine learning after 2018 (Figure 5). In keyword analysis, machine learning is the second most frequently used keyword, repeated 137 times. Looking at the top twenty rankings, "artificial neural network" and "deep learning" keywords rank seventh and eighth, respectively, with 73 and 56 repetitions.

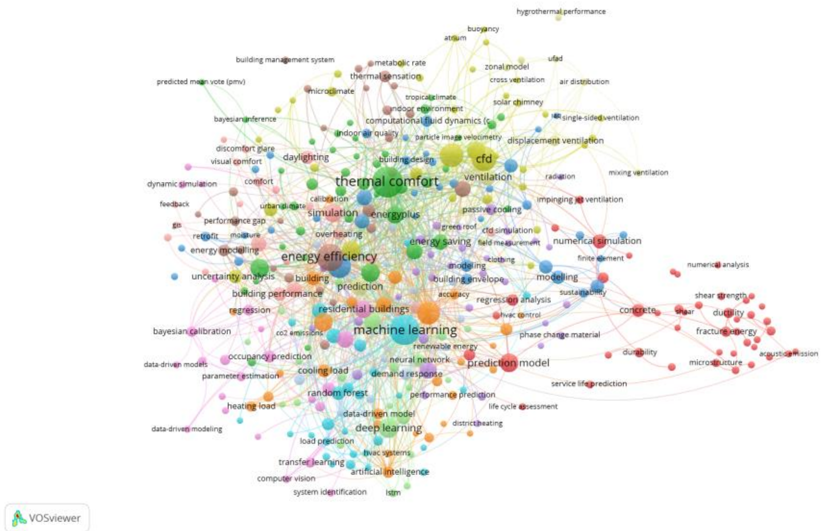

Figure 4. VOSviewer keyword analysis

TABLE 4. Keyword analysis and usage frequencies

Keyword	Occurences	Total Link Strenght
Thermal comfort	145	249
Machine learning	**137**	**251**
Energy efficiency	109	202
CFD	95	156
Natural ventilation	81	157
Energy consumption	80	159
Artificial neural network	**73**	**123**
Deep learning	**56**	**103**
Simulation	51	109
Prediction model	50	61
Climate change	49	86
Occupant behaviour	49	83
Building simulation	48	89
Sensitivity analysis	48	87
Computitional fluid dynamics	46	54
Prediction	43	101
Energy plus	41	93
Residental buildings	41	61
HVAC	40	87
Artificial neural network	**38**	**67**

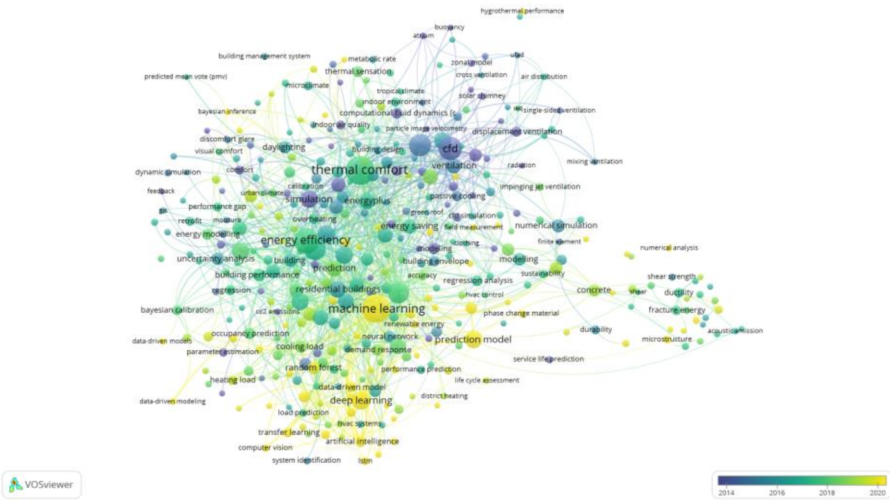

Figure 5. VOSviewer keyword analysis and distribution by years

4. Content Analysis

As mentioned in previous sections, content analysis of the selected thirty articles (Table 5) has been conducted in this section. Each publication listed in Table 5 has been analyzed according to the designated headings. With this tabulated data, a Sankey diagram has been created using the SankeyMATIC software. A Sankey diagram has been created using the data presented in the table (Figure 7).

TABLE 5. The 30 articles subjected to content analysis

	Yayın Adı	Year / Times Cited / References	Source	Data/Algorithm
1.	Multi-objective optimization of a building envelope for thermal performance using genetic algorithms and artificial neural network (Gossard et al., 2013)	2013/97/24	Energy and Buildings	ANN (Artificial Neural Network
2.	Extracting knowledge from building-related data - A data mining framework (Yu et al., 2013)	2013/59/64	Energy and Buildings	Data Mining (DM)
3.	The gap between predicted and measured energy performance of buildings: A framework for investigation (de Wilde, 2014)	2014/565/69	Automotion in Construction	Review
4.	Modeling heating and cooling loads by artificial intelligence for energy-efficient building design (Chou & Bui, 2014)	2014/234/54	Energy and Buildings	(SVR+ANN) / SVR Support Vector Regression
5.	Ensemble of various neural networks for prediction of heating energy consumption (Jovanovic et al., 2015)	2015/189/31	Energy and Buildings	FFNN (Feedforward Artificial Neural Network) / RBFN / ANFIS
6.	Short-term electricity load forecasting of buildings in microgrids (Chitsaz et al., 2015)	2015/118/41	Energy and Buildings	Self-Recurrent Wavelet Neural Network (SRWNN)
7.	Artificial neural network model for forecasting sub-hourly electricity usage in commercial buildings (Chae et al., 2016)	2016/219/35	Energy and Buildings	Bayes+ANN (Artificial Neural Network model with Bayesian regularization algorithm
8.	Forecasting diurrnal cooling energy load for institutional buildings using Artificial Neural Networks (Deb et al., 2016)	2016/159/41	Energy and Buildings	FFNN
9.	Data driven prediction models of energy use of appliances in a low-energy house (Candanedo et al., 2017)	2017/230/67	Energy and Buildings	GBM (Gradient Boosting Machine)
10.	A relevant data selection method for energy consumption prediction of low energy building based on support vector machine (Paudel et al., 2017)	2017/91/47	Energy and Buildings	SVM
11.	Random Forest based hourly building energy prediction (Wang et al., 2018)	2018/240/46	Energy and Buildings	Random Forest (RF)
12.	Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling	2018/227/69	Building and Environment	-

	behavior and machine learning (Kim et al., 2018)			
13.	Tuning machine learning models for prediction of building energy loads (Seyedzadeh et al., 2019)	2019/92/61	Sustainable Cities and Society	SVM
14.	Data driven parallel prediction of building energy consumption using generative adversarial nets (Tian et al., 2019)	2019/76/47	Energy and Buildings	GAN (Generative Adversarial Network)
15.	Study on deep reinforcement learning techniques for building energy consumption forecasting (Liu et al., 2020)	2020/98/50	Energy and Buildings	DRL (Deep Reinforcement Learning)
16.	Prediction and optimization of energy consumption in an office building using artificial neural network and a genetic algorithm (Ilbeigi et al., 2020)	2020/83/58	Sustainable Cities and Society	ANN
17.	Building energy consumption prediction for residential buildings using deep learning and other machine learning techniques (Olu-Ajayi et al., 2022)	2022/50/80	Journal of Building Engineering	DT (Decision Tree)
18.	A building energy consumption prediction model based on rough set theory and deep learning algorithms (Lei et al., 2021)	2021/48/39	Energy and Buildings	DNN (Deep Neural Network)
19.	A hybrid RF-LSTM based on CEEMDAN for improving the accuracy of building energy consumption prediction (Karijadi & Chou, 2022)	2022/14/133	Energy and Buildings	RF-LSTM
20.	Building energy prediction using artificial neural networks: A literature survey (Lu et al., 2022)	2022/21/71	Energy and Buildings	ANN
21.	Predicting future hourly residential electrical consumption: A machine learning case study (Edwards et al., 2012)	2012/218/33	Energy and Buildings	SVM
22.	Gradient boosting machine for modeling the energy consumption of commercial buildings (Touzani et al., 2018)	2018/188/42	Energy and Buildings	GBM
23.	Applied machine learning: Forecasting heat load in district heating system (Idowu et al., 2016)	2016/125/28	Energy and Buildings	SVM
24.	Short-term electricity load forecasting of buildings in microgrids (Chitsaz et al., 2015)	2015/118/41	Energy and Buildings	SRWNN (Self-Recurrent Wavelet Neural Network)
25.	Application of artificial neural network for predicting hourly indoor air temperature and relative humidity in modern building in humid region (Mba et al., 2016)	2016/114/48	Energy and Buildings	ANN
26.	Comparisons of inverse modeling approaches for predicting building energy performance (Zhang et al., 2015)	2015/108/54	Building and Environment	GMR (Gaussian Mixture Regression)
27.	Development of an occupancy prediction model using indoor	2016/105/23	Building and Environment	CART / HMM

	environmental data based on machine learning techniques (Ryu & Moon, 2016)			
28.	Predictive modeling for US commercial building energy use: A comparison of existing statistical and machine learning algorithms using CBECS microdata (Deng et al., 2018)	2018/101/43	Energy and Buildings	SVM / RF
29.	A hybrid model approach for forecasting future residential electricity consumption (Dong et al., 2016)	2016/102/52	Energy and Buildings	LS-SVM
30.	Energy forecasting for event venues: Big data and prediction accuracy (Grolinger et al., 2016)	2016/99/32	Energy and Buildings	ANN/SVR

Upon examining the research trends to observe building energy performance prediction and based on the analysis of the reviewed articles summarizing the last decade's studies, the following algorithm trends were observed: Among the 30 studied articles, 26 are focused on enhancing energy performance in existing buildings. Out of the remaining 4 studies, 2 are aimed at improving energy performance prediction during the design phase of new buildings, and the final 2 studies are academic review articles. The most frequently studied building types are educational and residential buildings, followed by commercial and office buildings (Figure 7).

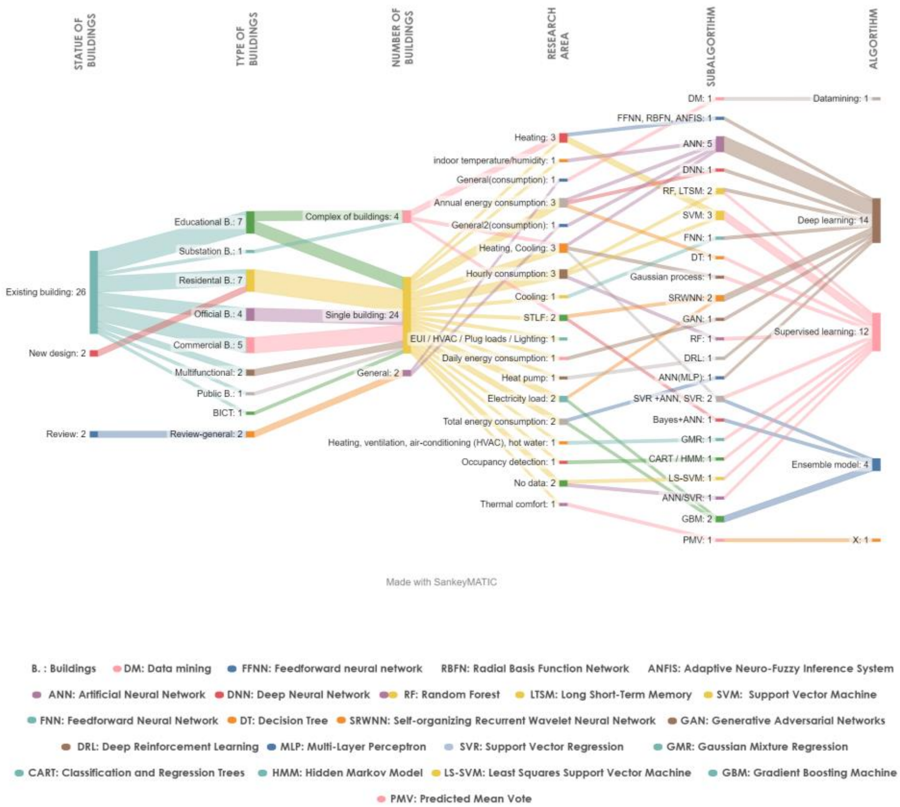

Figure 7. The Sankey diagram generated using the data from the selected thirty articles (Refer to Table 5 for algorithm abbreviations)

Other types represented by one study each include substation buildings, multi-purpose and public buildings. When viewed from a classification perspective, the utilized algorithms consist of 47% deep learning, 40% supervised learning, and 13% ensemble models.

5. Discussion

The correlation between the selected data and the accuracy of data classification, as well as the optimum execution time of the analysis with the chosen algorithm, are crucial factors in creating an accurate model for prediction.

Upon reviewing the conducted studies, it is evident that the selected data types and the combinations of algorithms used are generally not repetitive, and each study exhibits its unique characteristics.

The advancement of data collection methods is crucial for accurately analyzing the increasing volume of data and eliminating noise from low-quality data, ensuring that the chosen algorithm learns correctly.

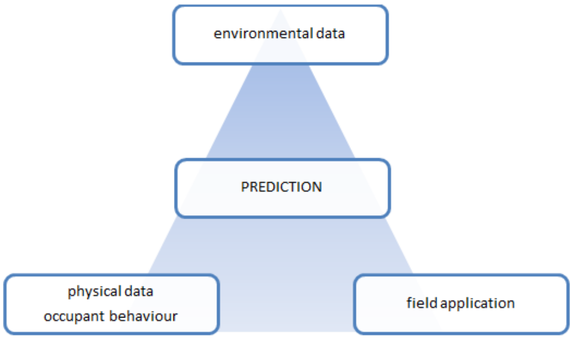

Figure 8. Parameters affecting the prediction

Over the past 10 years, studies have demonstrated the advantages of machine learning over traditional methods such as detailed physical modeling for building energy performance prediction (Figure 8,9)

When examining the research areas within the context of different building types (Figure 7), it is observed that each topic is repeated at most three times among the thirty studies. Similarly, this pattern is reflected in the types of algorithms used, with artificial neural networks being the most frequently utilized algorithm, appearing up to five times. It is notable that artificial neural networks are also employed as a component of ensemble models, such as SVR+ANN and Bayes+ANN.

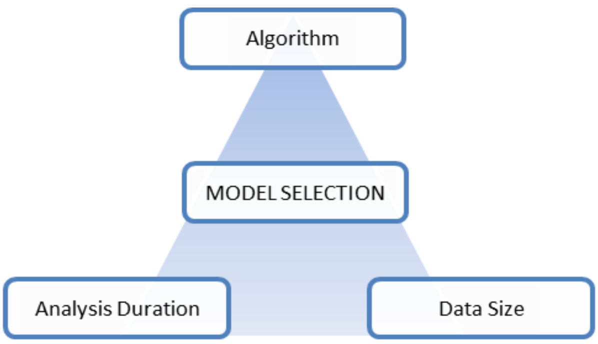

Figure 9. Parameters affecting the algorithm selection

The findings obtained in Chapter 4 demonstrate that in order to achieve more effective results in this field, open data sources should be established to shed light on future studies through the sharing of research data. The abundance of data and algorithm diversity used may not be instructive for future research.

6. Conclusions

This study has determined the machine learning algorithms and their utilization frequencies employed in the prediction of energy performance in buildings over the past decade, setting it apart from existing research. Simple statistical and regression methods (2012-2018) seem more suitable for predicting energy demand, yet they are not precise enough to capture the nonlinear behavior of building dynamics, especially for low-energy structures. In recent years (primarily after 2018), machine learning-based artificial intelligence models such as artificial neural networks and support vector machines have been utilized for energy demand prediction.

In addition to achieving good results with the proposed machine learning models, the analysis time is also significant. The necessity for each study to work with its specific data and identify an appropriate algorithm rather than building upon previous research, due to the nature of being structure-specific and lacking open data sources, presents a challenge to the sustainability of these studies.

Based on the obtained data from this study, it is observed that there is limited focus on aspects related to the design phase in energy performance prediction for buildings. The areas most emphasized include heating and cooling systems, electricity load forecasting, indoor air quality, and user behavior. Regarding predictive measures during the design phase, the variability in design and engineering details during implementation is a significant factor creating an energy performance gap, and research in this area is also constrained.

To ensure replicable outcomes in the generated machine learning models, it is essential to ensure that the dataset used for training completely represents the usage scenario or problem. Over the past years, statistical methods previously employed have given way to deep learning and ensemble models in the last decade.

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WALKABILITY

Digital parametric process for analyzing and evaluating walkability criteria in peripheral central regions of Belo Horizonte

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Abstract. According to one of the Sustainable Development Goals (UN, 2018), it is important for cities to be inclusive, safe, resilient, and sustainable. Therefore, it is necessary to prioritize pedestrians and promote active mobility, giving them priority and encouraging walking, as presented in the concepts of TOD (Transit-Oriented Development). Although the master plan suggests that areas located in the regional centrality of Belo Horizonte are enhancing active mobility, residents may still need to use individual or public transportation due to long distances when accessing basic services on foot. In peripheral areas of the city of Belo Horizonte, are there favorable walkability conditions for the residents? Thus, the aim of this research is to use digital technologies to investigate, through a parametric performative model, the quality of the existing routes, with a focus on the peripheral areas of the city. Based on the results obtained, it will be possible to conclude whether there are discrepancies between what is presented in the master plan and, ultimately, to identify potential solutions for the area based on metrics that qualify and enhance active mobility. These solutions may vary according to the specific needs of the location.

Keywords: *Walkability; Urban Data Analysis; Urban Design; Parametric Urbanism; Algorithmic Logic.*

ملخص. وفقًا لأحد أهداف التنمية المستدامة (الأمم المتحدة، 2018)، من المهم أن تكون المدن شاملة وآمنة ومرنة ومستدامة. لذلك، من الضروري إعطاء الأولوية للمشاة وتعزيز الحركة النشطة، وإعطائهم الأولوية وتشجيع المشي، كما هو موضح في مفاهيم TOD (التنمية الموجهة نحو العبور). على الرغم من أن المخطط الرئيسي يشير إلى أن المناطق الواقعة في المركز الإقليمي لبيلو هوريزونتي تعمل على تعزيز التنقل النشط، فقد لا يزال

السكان بحاجة إلى استخدام وسائل النقل الفردية أو العامة بسبب المسافات الطويلة عند الوصول إلى الخدمات الأساسية سيرًا على الأقدام. في المناطق الطرفية لمدينة بيلو هوريزونتي، هل تتوفر ظروف ملائمة للمشاة بالنسبة للسكان؟ وبالتالي، فإن الهدف من هذا البحث هو استخدام التقنيات الرقمية للتحقيق، من خلال نموذج أدائي حدودي، في جودة الطرق الحالية، مع التركيز على المناطق الطرفية للمدينة. بناءً على النتائج التي تم الحصول عليها، سيكون من الممكن استنتاج ما إذا كانت هناك اختلافات بين ما هو معروض في المخطط الرئيسي، وفي نهاية المطاف، تحديد الحلول المحتملة للمنطقة بناءً على المقاييس التي تؤهل وتعزز التنقل النشط. قد تختلف هذه الحلول وفقًا للاحتياجات المحددة للموقع.

الكلمات المفتاحية: *إمكانية المشى، تحليل البيانات العمرانية، التصميم الحضرى، العمران البارامترى، المنطق الخوارزمى.*

1. Introduction

Walkability is an essential concept in sustainable urbanization, aiming to promote walking as a means of transportation instead of relying on cars. The current Master Plan of Belo Horizonte (2019) aims to implement urban planning actions based on Transit-Oriented Development (TOD) principles for central areas. However, walkability is even more crucial in peripheral regions, which often lack adequate infrastructure and rely more on government actions to improve active mobility.

With the goal of developing an interactive model to assess walkability conditions in peripheral regions, this study adopted a methodology that included collecting georeferenced layers from the "BH Maps" portal, selecting the study area in the Vale do Jatobá region (characterized by its rugged topography and low Urban Development Index), and using metrics such as Walkability Score and Physical Proximity Algorithm (APF) for analysis and evaluation.

Based on the collected metadata, it was possible to build an interactive model that allows for micro and macro local analyses using the Urban add-on through the Grasshopper plugin. The model enables measuring and classifying a route according to the access conditions from a specific residential lot to a particular facility, as well as visualizing the level of walkability quality in specific areas through heat maps, such as access to the main bus station in the region. The analysis results will help identify areas lacking public facilities, shops, and services in the region, as well as evaluating critical points in roads that do not meet the necessary conditions for active mobility.

However, constructing the model also brought to our attention inherent contradictions that can arise between importing urban planning models and their possibilities of effective local actions. Therefore, we believe this study can be especially useful for policymakers to develop intervention projects focused on active mobility, taking into account specific contexts and optimizing resource allocation for the revitalization of peripheral centralities.

1.1 URBAN LEGISLATION

In the current Master Plan of Belo Horizonte, approved by Law 11.181/19, regional centrality areas were established, where one of the main principles of development focuses on active mobility. To achieve this, the government aims to encourage the use of non-motorized transportation and promote walkability in these areas. However, do these areas designated as regional centralities actually have suitable pedestrian walkability conditions?

Therefore, the objective of this research is to quantitatively and qualitatively assess the walkability conditions in these centrality areas.

For quantitative analysis, a digital parametric method will be used to model and evaluate the existing conditions through two metrics. The first one is called "Walkscore" (Walk Score, 2021), which, according to Carr et al. (2011), is an algorithm capable of generating scores based on distances from a specific location and the closest points of service and commerce. These points can be classified into five categories (education, commerce, entertainment, and recreation). These categories are weighted equally and then summed, resulting in a unique index that can classify the walkability of the desired location. For example, if the closest service for a certain category is 400m away (approximately a five-minute walk), then the maximum number of points will be assigned to the location in that category. The score decreases as the distance increases up to 1.6 km (which is approximately a 30-minute walk), and no points are assigned to services that are at that distance. All categories have the same weight, and their respective points are summed and then normalized to generate a score between 0-100, allowing for the classification of walkability in the desired location (see Table 1). The number of nearby available services and their respective distances to nearby residences are the main parameters capable of determining optimized walkability.

TABLE 1. Walkscore Value Classification. Source: Walkscore, 2014

90-100	*Walker's paradise*
	Daily routes do not require a car
70-89	*Very walkable*
	Most routes can be completed on foot
50-69	*Somewhat walkable*

	Some routes can be covered on foot
25-49	*Car-dependent*
	Most routes require a car
0-24	*Car -dependent*
	Almost all routes require a car

Thus, if the starting point is located 400m away (5 minutes walk) from its target, it will be assigned a final value of 1. As the distance from a starting point to its final destination approaches 1.6 km (20 minutes walk), its score decreases. The value 0 is assigned to distances where the closest target is greater than or equal to 1.6 km (as shown in Table 2).

TABLE 2. Reference values for calculating physical proximity measures.

Índex	*Meaning*
1	Excellent proximity - less than 5 minutes walk
0,5	Good proximity - 10 minutes walk
0	Proximity disregarded – more than 20 minutes walk

Indeed, considering the influence of inclinations on the route (time and effort) during walking, the APF allows for applying penalties to inclined routes. Thus, the steeper the incline of a certain segment, the greater the penalty applied to that route. For example, if we consider a flat route with a distance of 400m, it will be assigned the maximum index (1). However, if another route has the same distance of 400m but with an inclination of 10%, the final value assigned to that route will be 0.9. This is because it will be penalized by 10%, corresponding to its slope. Therefore, the APF aims to measure and assess the walkability of a specific area through the calculation of routes with the shortest distances to all targets of the same category, considering their physical distances, inclinations, and applying their respective penalties, allowing each category to receive a partial index. The total index is then obtained by averaging these partial indices.

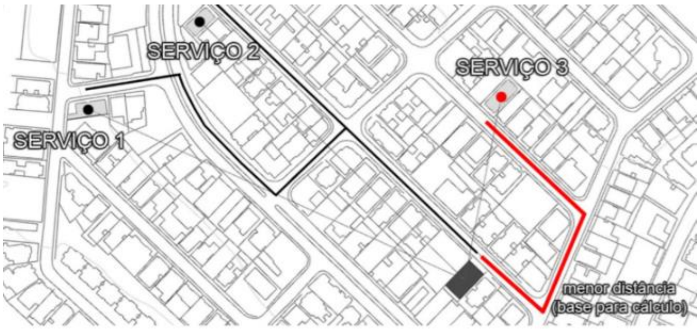

Figure 1. Logic of the APF Calculation. Source: LIMA, Fernando, 2017.

Thus, for different targets: the algorithm calculates the shortest physical routes to all targets (services) in the desired category, then identifies the service with the shortest physical distance (in red) and measures its proximity to the origin based on that distance (including possible inclinations and their respective penalties) as represented in Figure 1.

To perform a qualitative analysis, it will be necessary to focus on a specific context, an area of the Jatobá Macroplan in the Barreiro Region. As a method for qualitative analysis, we propose using digital parametric modeling through the design of analysis and evaluation algorithms for the established criteria. The advantage of implementing parametric systems in urban planning lies in "maintaining the model's ability to change throughout the entire design process and allowing the generation and testing of a large number of versions within a controlled design environment, based on simple changes in values of specific parameters" (LIMA, CURY; RIPPER, 2015). Ultimately, they also allow visualization of the entire project, which enables understanding how the new proposed interventions are being applied and their functionality. With the results to be achieved, it will be possible to assist those responsible for space production in identifying the roads in the centralities that do not promote walkability, offering objective analyses for possible infrastructural interventions, or in the revision of areas intended for centralities that do not have conditions for the effective implementation of active mobility. These results can be used to guide urban restoration projects, considering that financial resources have already been allocated for this purpose, established in the Master Plan through the creation of the Centralities Fund where resources will be allocated for works in these planned areas.

2. Methodology

2.1. AREA SELECTION FOR ANALYSIS

The selected study area is within the Macroplan of Jatobá in the Barreiro Region, encompassing the Barreiro neighborhood and extending to the vicinity of Diamante Station, which is approximately 3.5 km away from the neighborhood. The Barreiro Region, where the study area is located, is considered a peripheral region of Belo Horizonte with around 280 thousand inhabitants, and it can be regarded as the second busiest area in the city after the commercial center. The challenges faced in this locality arise from the fact that the road infrastructure and public transportation services have not kept pace with the region's development and growth. Many residents work in the city's central area and require easy access to public transportation and other services.

There is a small extension beyond the Barreiro neighborhood selected for analysis, which leads directly to Diamante Station. This is because it is the closest station for residents, making it difficult to connect with local neighborhoods, other bus stations, and the central region of Belo Horizonte. Another recurring factor in the area is its topographical characteristics, with many hills that, combined with a limited availability of basic services and few public transportation options, further hinder accessibility and active mobility for residents.

The analysis of this area will be crucial in identifying walkability conditions and understanding the challenges faced by the local population in terms of pedestrian infrastructure and active transportation. By addressing these issues, the study can contribute to proposing interventions and improvements that promote better mobility and a more pedestrian-friendly environment in the Barreiro Region.

1.1. MODELING OF THE SURROUNDINGS

For the modeling of the location, metadata was collected from the "BH Map" (as we can see in the Figure 2) website based on the categories that will be used for the analysis and modeling of the area, including: (1) Bus Stops, (2) Bus Station, (3) Schools, (4) Hospitals, (5) Health Centers, (6) CTM Lots, (7) Road Slopes and (8) Buildings in the surroundings.

These metadata provide essential information about the transportation infrastructure, educational and healthcare facilities, land use, and the topography of the area. By incorporating these datasets into the modeling process, it becomes possible to analyze and assess the walkability and accessibility of different services and amenities in the location, as well as understand how the surrounding built environment influences mobility patterns. This data-driven approach enables a comprehensive evaluation of the area's pedestrian-friendliness and informs potential interventions and improvements to enhance active mobility and overall urban sustainability.

After downloading each of this information, they were imported into the QGIS software to make a more specific area of study. After the clipping, it was possible to insert the shapefiles into Grasshopper.

The shapefile files were imported into Grasshopper using the Urbano plugin, which allows for the reading of shapefile files through metadata, enabling the modeling of the study area's surroundings and conducting the desired analyses. For the modeling of buildings, the Urbano plugin was used, utilizing the height metadata from the shapefiles to generate the volumetric representation of the entire study area's surroundings.

1.2. APPLICATION OF WALKABILITY ANALYSIS CRITERIA

Subsequently, it was necessary to extract a dataset with the respective inclinations of each section of the pathway to apply the weighting formula, which would present the quality of the route. The formula used would consider the distance between a starting point and its final destination and apply a certain penalty value based on the incline of each section. For instance, if the route is less than 400 meters, it would receive a score of "1" (adequate route); if it falls between 400m and 1600m, the score would be "0.5" (somewhat suitable route); and if it is longer than 1600m, it would receive a score of "0" (inadequate route). Furthermore, penalties should be applied for each section, for example, if a 400m route has an incline of 10%, a value of "-1" would be subtracted from its final score, resulting in a score of "-0.9". Similarly, a 20% incline would result in a subtraction of "-2", and so on, we can see this in the figure 2.

Thus, incline values for each route were extracted through a datalist, and some categories were scored for analysis, namely (1) Schools, (2) Bus stops, (3) Bus stations, (4) Metro stations, (5) Hospitals, and the (6) starting point. To measure the distance between the starting point and the final destination, the urban plugin was also used. It generates the pathways and allows different possibilities for accessing the desired location. By moving the points within the urban network, it can generate routes that adapt to the area.

Finally, a color scheme, ranging from red (no accessibility) to green (good accessibility) was employed to provide a graphical representation of the pathway quality. Different shapes were used to represent each category of essential services, the starting point, and numbering was applied to identify the score of each location more conveniently in the list. This approach allows for a quick visual assessment of the accessibility and walkability of different areas within the study region.

3. Results

Based on the data obtained from BH Maps and the parameters related to promoting active mobility, it is possible to analyze the walkability quality in the area. The analysis reveals that the access of residents to essential services in the region does not provide means that encourage their comfort, necessitating the use of individual or public transportation in most cases to access what they need. This is because these locations are at a considerable distance from their residences and/or have steep inclines, which present significant obstacles for people, as not everyone can complete the journey due to their limitations. Figure 2 shows the quality of access to essential services in the region with the applied metrics. Warmer colors represent areas that are difficult for residents to access due to distances exceeding 1.6 and influenced by local inclines, while scores shown in green indicate pathways that meet accessibility metrics.

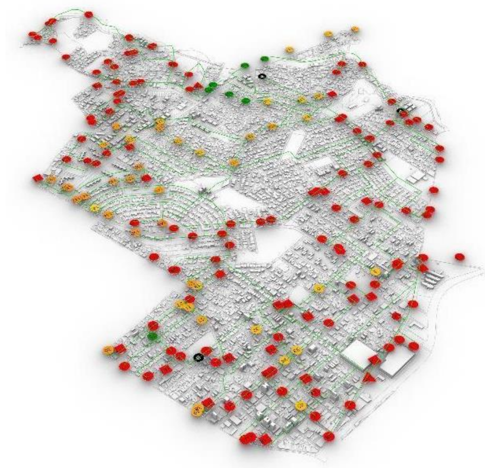

Figure 2. Quality of access to basic services in the region with applied metrics. Source: Authors, 2023**.**

Parametric modeling also allows for the generation of different pathways within the urban fabric, enabling paths to adapt according to the starting point and providing a greater number of analysis possibilities. Figure 6 will demonstrate the generated pathways and the corresponding results presented for each of them. The colors ranging from red to green represent the lowest level of quality (red) to the most suitable (green), and the black point represents the initial starting location. A brief analysis reveals that the most viable points are those located in the vicinity of the starting point, while the others are largely unfeasible.

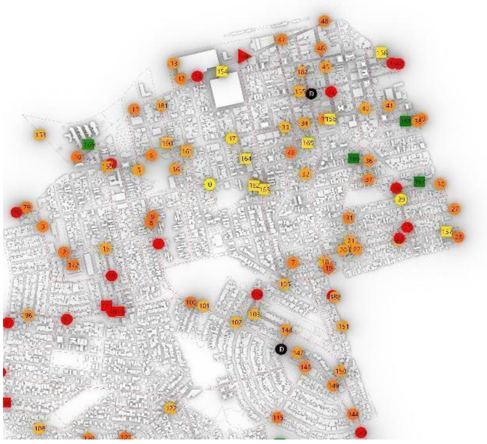

Figure 3. Identifiers of the analyzed categories. Source: Authors, 2023.

In Figure 3, a strategy for better identification of the analyzed categories is demonstrated. Symbols were used to easily identify them in the model, with circles representing bus stops, squares for schools, triangles for bus stations, and hexagons for hospitals and health centers. This method of walkability analysis was also applied in another study area during a workshop at Digital Futures with the participating students. The goal was to analyze the active mobility in the area in relation to the services available to the residents. The chosen location is situated in a central region of São Paulo, and the obtained walkability analysis results were satisfactory, allowing a better understanding of how the services in the area relate to the local residents.

Thus, the color gradient allowed for a clear understanding of the most accessible services (within a distance of up to 400m), less accessible services (distance between 400m and 1.6km), and the services that are not accessible (distance greater than 1.6km), making it easier to comprehend the relationship between pedestrians and residents with the distribution of basic services in the area. In Figure 6, an example of accessibility to public transport in a central region of São Paulo is shown. The model generated a color gradient that represents the degree of accessibility (characterized as accessible, less accessible, and not accessible), similar to the model used in the research, and likewise generated shorter pathways to each of these locations within the urban fabric.

Figure 4. Accessibility analysis of public transportation in a cutout of downtown São Paulo. Source: Authors, 2023.

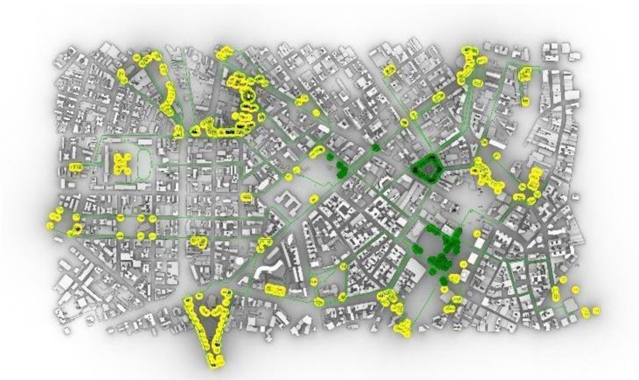

Figure 5. Accessibility analysis of leisure spaces in a cutout of downtown São Paulo. Source: Authors, 2023.

The advantage of using parametric methods for performance analysis lies in the ease of changing categories. Once the parameters and metrics are applied, the results automatically update according to the distribution of points related to the specific category. Figure 5 shows the walkability analysis for a different category from Figure 4 Here, the study focuses on leisure areas within a space located in downtown São Paulo. Using parametric methods allows for a flexible and dynamic approach to analyzing various aspects of urban planning and walkability. It enables quick and efficient exploration of different scenarios and criteria, making it a valuable tool for decision-making and improving the design and functionality of urban spaces.

4. Discussion

Based on the data obtained from BH Maps regarding the parameters that enhance active mobility (Walkscore and APF), it becomes possible to analyze the walkability quality in the study area. From this analysis, it can be concluded that the residents' access to essential services in the region is not providing means that encourage their comfort. In many cases, they need to rely on individual or public transportation to access what they need daily.

There are obstacles between their residences and the respective locations of essential services that make it difficult for them to access these services easily. The Plano Diretor of Belo Horizonte addresses local centralities in the study area, which are expected to act as facilitators, providing a variety of elements to meet the needs of the residents, such as access to public transportation, hospitals, healthcare centers, schools, parks, and more.

However, after analyzing the area using mobility parameters, it was observed that, in practice, the distribution of such services mostly occurs at a distance greater than 1.6 km, which causes discomfort for pedestrians. Moreover, the local topography further hinders the residents' relationship with other locations due to the steep slopes present in the region. For older people or individuals with health limitations, navigating the area can be extremely challenging or even impossible.As a result, there seems to be a discrepancy between the Plano Diretor's expectations of active mobility in areas with local centralities and the reality of the model results, where only a small portion of residents can easily access nearby services.

The information acquired from these analyses can be of paramount importance for the city's sidewalk planning. With the model's help, it is possible to understand which areas within the neighborhood face more significant mobility challenges and propose improvements to the routes, if feasible. Additionally, it opens the possibility to rethink the distribution of essential services within the neighborhood. If the majority of residents have difficulties accessing these services due to distance or local topography, a redistribution of these services to more accessible areas is crucial. This way, any omissions of necessary services can be addressed, and a more pragmatic redistribution can be made based on the area's specific needs. The ultimate goal is to provide more suitable pedestrian routes for residents to access essential services with higher quality, thereby contributing to more sustainable cities in line with the United Nations Sustainable Development Goals (SDGs) and the concept of Transit-Oriented Development (TOD).

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2.B.

BUILDING INFORMATICS AND PARAMETRICS - II

USE OF GENERATIVE SYSTEMS TO CREATE SEMI-PUBLIC SPACES IN CONTEMPORARY NEIGHBORHOOD TEXTURE

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Abstract. Cul-de-sacs are examined together with the urban reading in Siverek. Studying cul-de-sacs is instrumental to understand the morphology of Islamic cities. Cul-de-sacs provide a buffer zone between main roads and houses. For this reason, both the privacy phenomenon, which is one of the important issues for Islam, and the safe space need of the residents are important spatial elements. Until 1968, the city of Siverek developed organically within a compact texture of narrow and curvilinear streets, open courtyards, and a adjacent high-walled residences. In this texture, many semi-private cul-de-sacs have an organic form, which is one of the critical spatial elements of the city. Residential walls or courtyard walls form the natural line of traditional streets. In this study, typological analyses of cul-de-sacs were made, and form grammar, a productive method used to analyze architectural language, is included. It aims to examine the relationship between residential settlement and street using the data set created with shape grammars and to make urban propositions for neighbourhood structures in the context of a cul-de-sac using L-systems in the next step. Some parameters have been determined in forming cul-de-sacs that form the urban texture. These parameters were transferred to the model using digital tools. A method thought to be used in urban production has been put forward. The most important reference of this method is dead-end streets.

Keywords: *Urban design, rule-based design systems, semi-public space, cul-de-sacs, Siverek.*

USE OF GENERATIVE SYSTEMS TO CREATE SEMI-PUBLIC SPACES IN CONTEMPORARY NEIGHBORHOOD TEXTURE

ملخص. يتم فى هذا البحث فحص الطرق المسدودة جنبًا إلى جنب مع القراءة الحضرية في سيفيريك. تعتبر دراسة الطرق المسدودة مفيدة لفهم مورفولوجية المدن الإسلامية. توفر الطرق المسدودة منطقة عازلة بين الطرق الرئيسية والمنازل. ولهذا السبب، تعد ظاهرة الخصوصية، التي تعد إحدى القضايا المهمة في الإسلام، وحاجة السكان إلى المساحة الآمنة، عنصرين مكانيين مهمين. حتى عام 1968، تطورت مدينة سيفيريك عضويًا ضمن نسيج مدمج من الشوارع الضيقة والمنحنية، والساحات المفتوحة، والمساكن المجاورة ذات الجدران العالية. في هذا النسيج، العديد من الطرق المسدودة شبه الخاصة لها شكل عضوي، وهو أحد العناصر المكانية المهمة للمدينة. تشكل الجدران السكنية أو جدران الفناء الخط الطبيعي للشوارع التقليدية. في هذه الدراسة، تم إجراء تحليلات نمطية للطرق المسدودة، وتم تضمين قواعد النحو، وهي طريقة إنتاجية تستخدم لتحليل اللغة المعمارية. ويهدف إلى دراسة العلاقة بين المستوطنة السكنية والشارع باستخدام مجموعة البيانات التي تم إنشاؤها باستخدام قواعد النحو وتقديم مقترحات حضرية لهياكل الأحياء في سياق طريق مسدود باستخدام أنظمة L في الخطوة التالية. تم تحديد بعض العوامل في تشكيل الطرق المسدودة التي تشكل النسيج الحضري. تم نقل هذه المعلمات إلى النموذج باستخدام الأدوات الرقمية. لقد تم طرح طريقة يعتقد أنها ستستخدم في الإنتاج الحضري. وأهم مرجع لهذه الطريقة هو الشوارع المسدودة.

الكلمات المفتاحية: *التصميم الحضرى، أنظمة التصميم القائمة على القواعد، المساحات شبه العامة، الطرق المسدودة، سيفيريك.*

1. Introduction

Shape grammars include design languages and styles, addressing the basic concepts of various design fields, primarily architectural design (Behbahani and Gu, 2018). It can be introduced as a way of describing and even deriving an algorithmic structure, to a certain extent, with a rule-based structure (Liu, Gegov, Coceo, 2016). Although shape grammars have descriptive and generative properties, they are generally used to derive patterns, spatial topologies and two- or three-dimensional compositions (Eilouti, 2019). Shape grammar uses points, lines, planes and geometric bodies, which are the essential elements of geometry. Transformations, such as reflection, shift, rotation, and sizing, or operations, such as addition and subtraction, are used in the design. A shape grammar is a set of shape rules applied step by step to produce a design language or design set (Stiny, 2006). In this study, several analyses were conducted by using shape grammars, with the purpose of describing several urban elements including streets, cul-de-sacs, houses, neighbourhood borders, construction materials.

Throughout the study, it has been examined how cul-de-sacs takes place daily life in the context of Siverek. Oral interviews were done with users, photographs of the streets were taken, and an archive was created, with the maps of the neighbourhoods with dead-end streets were drawn, the types of dead-end streets were determined, the importance and functioning of the streets were conveyed with diagrams. In the context of Siverek, the characteristics of cul-de-sacs, their values, their place and importance in the space hierarchy were examined. The lack of semi-public spaces in urban designs were emphasized, and the absence of the missing semi-public ring in the space hierarchy in new designs was determined as a problem.

The following section briefly introduces related works done in the context of urban studies, generative properties and types of algorithms. Subsequently, the paper informs the context of Siverek, located in the southeast of Turkey featuring unique street patterns and architectural styles. The methodology section starts with flowchart that explains the steps taken to conduct this study, continues with the methods applied and ends with the findings of generative productions. The discussion part delves into the theoretical exemplifications of the use of generative tools in urban design and planning with different stakeholders enabled to participate thanks to the parameterization of urban rules learned from existing traditional urban patterns.

2. Literature Review

In urban planning, modelling a city requires the design of a transportation network and often leading to a masterplan that tracks urban area, population growth while considering environmental impacts. Additionally, building appearances are essential in compliance with historical, aesthetic and legal rules. But a roadmap must always be designed initially to create an infrastructure for accessing houses, for which many buildings must be created as well.

L-systems are used for transportation networks when modelling cities. To create a roadmap in Manhattan, Parish and Müller (2001) designates an L-system from various image maps, with input data including land-water boundaries and population density. Their system creates a highway and street system, dividing the land into parcels and creating the appropriate geometry for the buildings in the respective parcels.

In some cases, shape grammars are combined with space syntax analysis focusing on unplanned areas and urban regeneration projects in cities with organic textures. Strategic Planning Framework (SPF) for Jeddah defines an approach to rehabilitate many unplanned sites in the city (Ducla-Soares, 2007). First, the condensed and isolated core of the settlement is detected by local accessibility analysis. Based on this, a strategy is decided to realign the smaller segments which are connected to the larger structure of city-wide routes. Therefore, SPF forms the basis of a system that can capture some features of the existing urban fabric and applies them in contemporary urban planning and architectural design.

Koltsova, Tuncer and Schmitt (2013) presents a visibility analysis tool for 3D urban environments and possible applications of it in urban design. It uses a ray casting method to analyse the visibility of facade surfaces from a particular vantage point and in a particular urban setting, with buildings and roads. It also provides information about the buildings/facades that look best from the road sections.

3. Context: Siverek's Cul-de-sacs

Siverek is a town in the province of Şanlıurfa in the Southeastern Anatolia Region of Turkiye To the east of the district is Karacadağ, at a height of 1919 meters, and to the west is the Euphrates River, which forms the natural borders of the city. The city is located in a flat area at the foot of Karacadağ. Its geography and topographic structure have affected the morphology of the town. Except for the castle in the centre, there is no significant elevation in the settlement area. The city, established on a flat site, developed radially in all directions since it did not encounter any obstacles during growth.

Siverek houses are in the group of southeastern Anatolian Houses, and their formation is influenced by culture, lifestyle, large family structure, climate and geography. Basalt stone, which is densely found due to the Karacadağ volcanic mountain activities in the region, was used as the dominant material in Siverek architecture. Cul-de-sacs were examined together with the urban reading in Siverek. The dead-end street is important, especially in the morphology of Islamic cities. Dead-end streets have the characteristics of a transition zone (buffer) between the main roads and the house (Kalak, 2021). For this reason, both the privacy phenomenon, which is one of the important issues for Islam, and the safe space needs of the residents are important spatial elements.

Until 1968, the city of Siverek developed organically in a compact texture of narrow and curvilinear streets, open courtyards, and adjacent high-walled residences. In this texture, there are many semi-private cul-de-sacs, which have organic form, one of the city's important spatial elements. Residential walls or courtyard walls form the natural line of traditional streets.

In this study, typological analyses of dead-end streets have been made, and form grammar, a productive method used to analyze architectural language, is included. It aims to examine the relationship between residential area and street by using the data set created with shape grammars and to make urban propositions for neighbourhood structures in the context of dead-end streets using L-systems in the next step (Figure1).

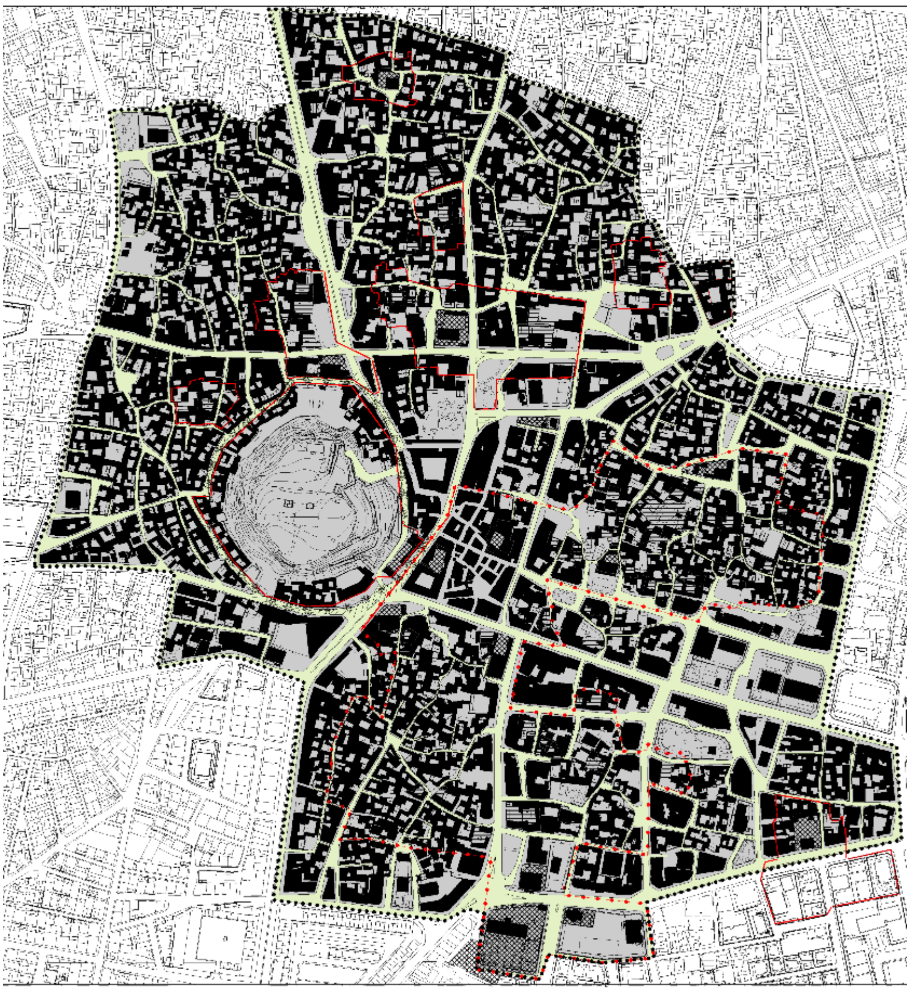


Figure 1. Şanlıurfa Metropolitan Municipality conservation plan (Ş.M.M, 2016).

4. Decoding the Pattern of Semi-Public Spaces in Siverek

4.1. PROCEDURE

It is explained how the work done in the flow diagram is progressed. The diagram in which the process is conveyed also gives information about the method of the study and the tools used. The diagram, which includes the interventions for the study, made it easier for us to understand the study (Figure2).

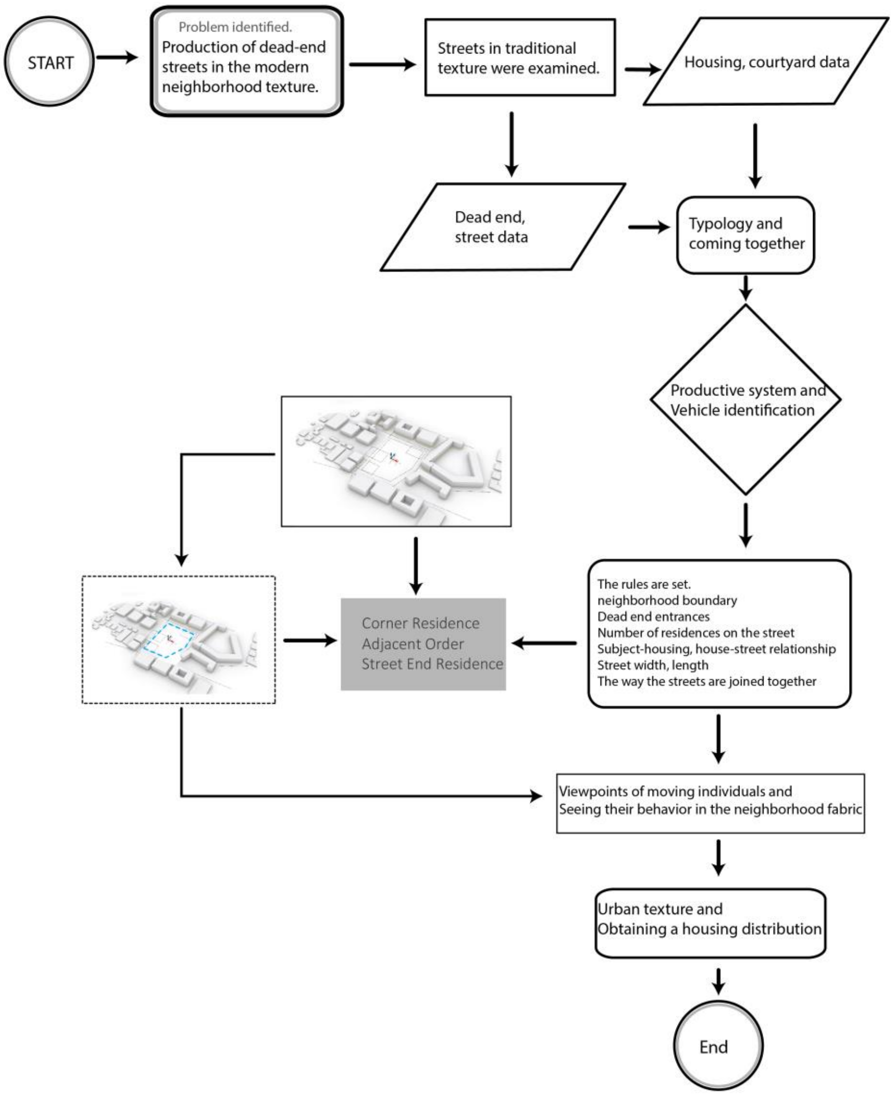


Figure 2. Flow Chart

4.2. ANALYSIS

After collecting the data on the area, the land was tested/observed/explored? one-on-one in order to bring the data together in a meaningful way and create networks of relationships. By visiting / conducting visits to the area at different times of the year and at different times of the day, movement in the tissue and daily life was observed. The role of dead-end streets in the life cycle was examined. *Cul-de-sac formations* were defined as positive areas with some data and observations. The methods of transferring the semi-public spaces formed were examined (Figure3).

Figure 3. Neighborhood texture and some examples of cul-de-sacs.

In order to create a dataset, street elements, some parameters that affect the formation of the street, the relationship between the house and the street, the practices of acting in the semi-public space, and the contact status of the houses with the street were tried to be processed into form grammars. The process was controlled by transferring the street data to the digital environment, which was then advanced in the computer environment.

Street form
Number of residences
Building materials
Wall height
Building order
Neighbourhood boundary

Neighbourhoods worked, and the number of cul-de-sacs in these neighbourhoods was determined (Table1).

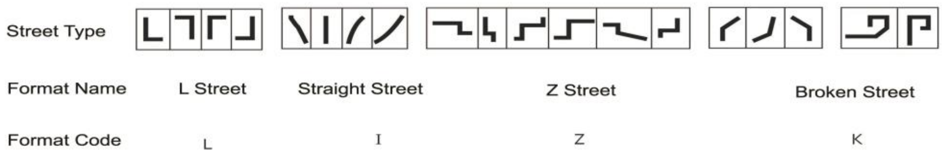
TABLE 1. Number of dead-end streets in neighborhoods

Neighbourhoods	Hayriye	Camıkebir	Hamidiye	Gülabibey	Kale	Hasan Çelebi	Şair İbrahim
Number of cul-de-sacs	15	17	14	20	6	9	2

4.2.1. Street Form

Street types were tried to be determined and classified, and names were given to these classes. The symbols determined the names of these classes, and it was the beginning of creating a critical flow path of working as a set of dictionary elements. (Table2)

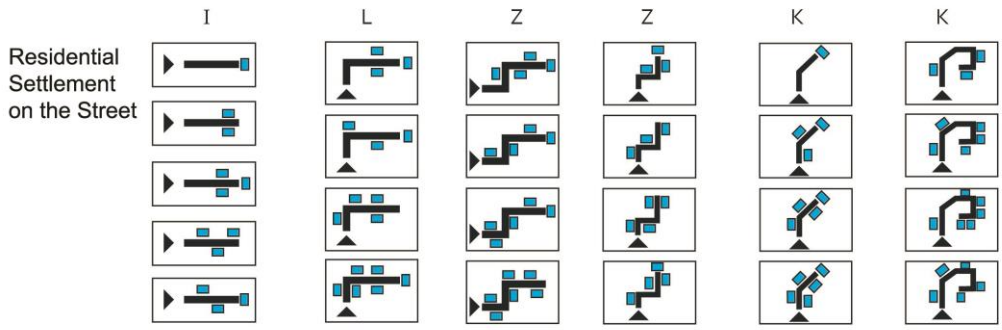
TABLE 2. Cul-de-sac forms in neighbourhoods



4.2.2. Settlement of Houses

After the stylized street forms, the entrance direction of the streets was determined, and the settlement of the houses on the streets was tried to be created on a systematic plane while the number of houses was changed. The residential settlement on the street was created with the data obtained from the area. The house layout at the end of the dead-end street was one of the essential data guiding the use of the street. In some street formations, it was seen that there were small squares at the end of the street. These areas sometimes became playgrounds and sometimes became where street users used to do their daily work (washing wool, harvesting/processing? pepper…) (Table 3).

TABLE 3. Residential settlement on the street



How the cul-de-sac is associated with the houses on that street affects the structure of the street and appears as important data when determining the vocabulary (Figure 4).

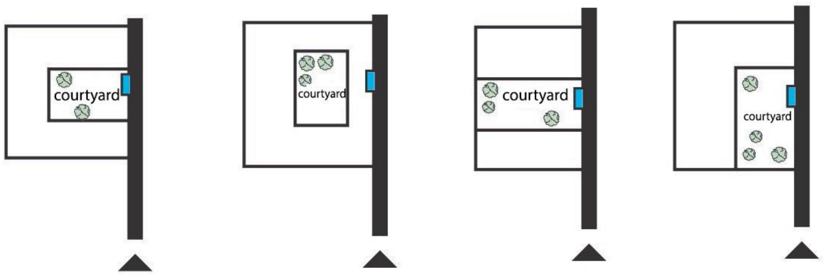


Figure 4. Examples where we can see the courtyards and entrances of some residences.

The housing contact with the street is considered an essential input for using the street. Situations such as whether the entrance door opens directly to the courtyard or enters the courtyard through another space create differences in the residential street organization (Figure 5).

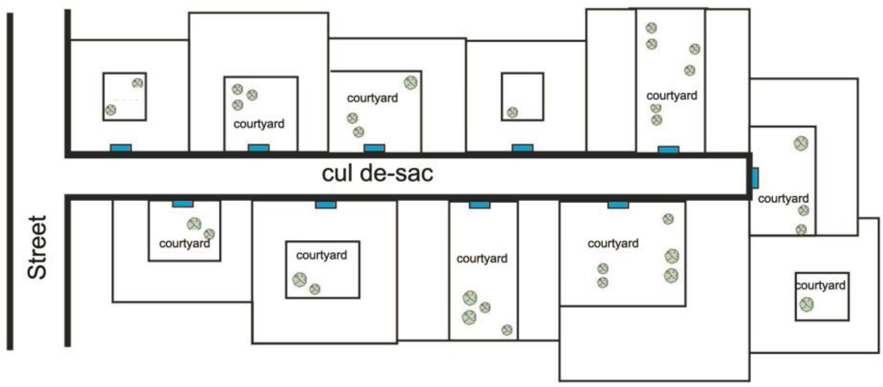


Figure 5. Houses on a cul-de-sac and the relationship between courtyard, street and house

4.2.3. Street Section

The outer walls of the houses define the boundaries of the street and contain differences in the contact of the houses with the street. There are some small solutions for the contact of a person walking in the private area of the houses on the street, and care is taken not to place the entrance door of the houses directly opposite the door of the house the entrance doors are placed on the street as surprisingly as possible. Street doors are left open during the day, and safe spaces are created for children to play in the dead end.

Houses come into contact with the street, with the garden wall, and sometimes with the building wall, and the way they are included in the house may vary. It includes different formations, such as entering the courtyard directly from the entrance door and entering the entrance hall, and is included in the building with the iwan (Figure5) (Figure6)

Figure 6. Cul-de-sac section.

4.2.4. Visibility Analysis of Cul-de-sacs

It aims to calculate the amount of surface that an individual can see and the distance he can see in the neighbourhood texture. In this context, a visibility analysis was tried to be created in Grasshopper. The analysis circuit aims to provide data on how much of the area an individual will scan while touring and not enter areas such as a dead-end street if the agent is not a member of that neighbourhood (Figure 7 and 8).

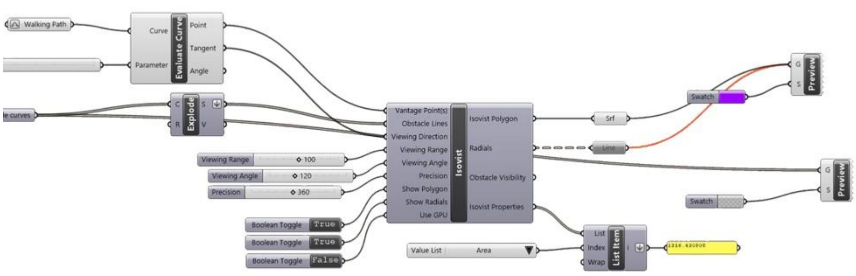


Figure 7. Visibility analysis Grasshopper circuit.

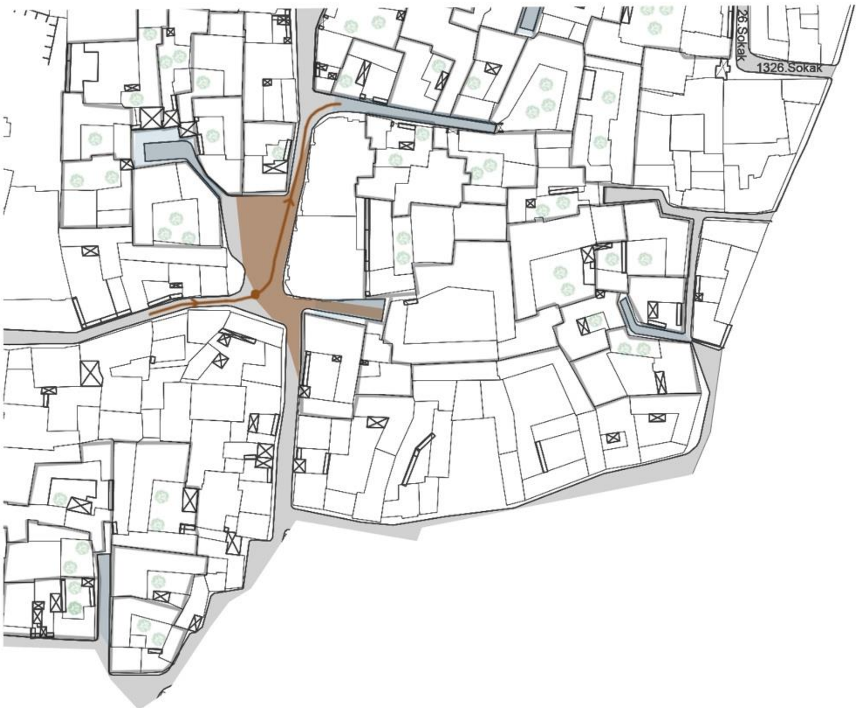


Figure 8. Example of area scanned by visibility analysis.

4.3. RULE-BASED DESIGN SYSTEM

Throughout the process, the paper deals with the settlement situations associated with the neighbourhood fabric. The main aim was to review on the street formation and the housing and visibility situations.

4.3.1. Housing Units

While creating the neighbourhood texture, the layout, form, and size of the houses are essential parameters in the formation of the neighbourhood. These parameters of the houses also determine the formation of their streets. The courtyard forms and sizes of the traditional houses with courtyards also contributed to the process. The facades of the houses facing the street, the facades facing the courtyard, the number of floors, and the total built area were processed in Grasshopper, and some of the housing variations that could be created by changing these parameters were seen. (Figure9) (Figure10)

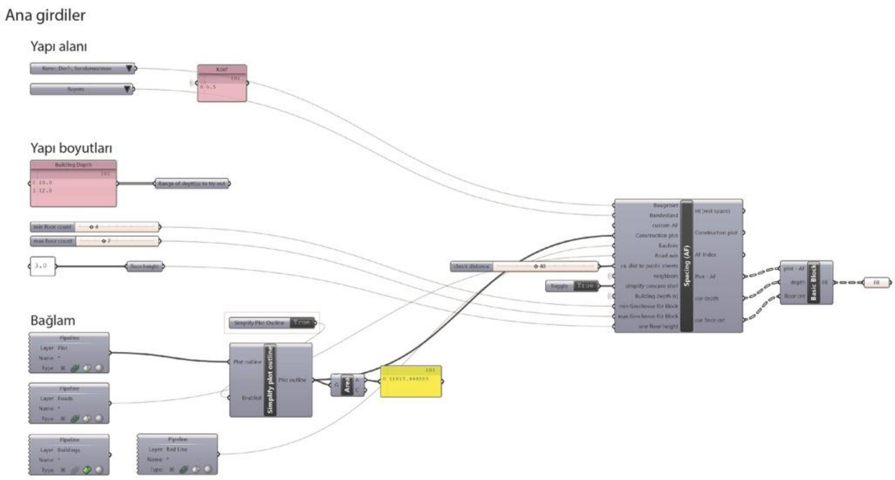


Figure 9. Grasshopper circuit for housing formation

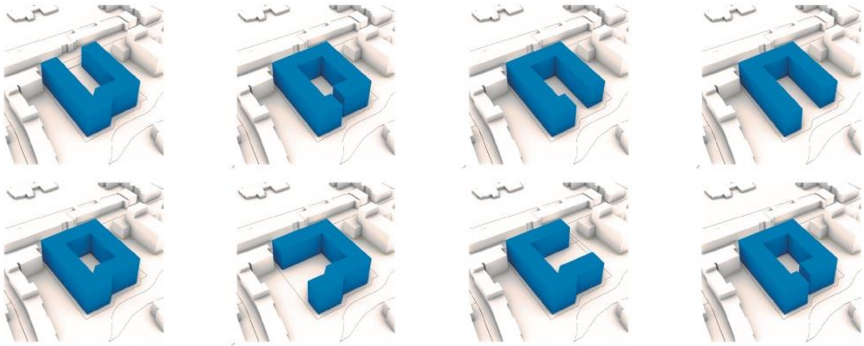


Figure 10. Some courtyard housing formations

4.3.2. Generation of Rules

The study focuses on generative systems, utilizing morph grammars and L-systems. The objective is to generate street and cul-de-sac networks for new neighbourhood formations using a dataset created for morphological grammars, along with defined rules. The grammar rules used in the study are as follows:

- defining the boundaries of the neighborhood,
- identification of entrances to cul-de-sacs
- determining the number of houses on each street,
- defining the relationship between subject-housing and housing-street,
- associating street width and length,

- describing the way streets are interconnected.

In addition to these rules, the study also attempted to include corner housing, end-of-street housing, and layout status in the analyzed texture and the generated texture.

Two neighbourhoods, Haliliye and Hamidiye, were selected as reference areas for the analysis due to their significant number of cul-de-sacs and their unique urban texture. The boundaries of these neighborhoods were determined, and corner points were marked. The streets, dead-end streets, and roads within these neighborhoods were carefully examined and mapped (Figure 11, left). The streets, cul-de-sacs and roads of these neighborhoods were examined and shown on a map (Figure 12, right).

Figure 11. Neighborhood boundaries of Haliliye and Hamidiye in Siverek (left). Main roads of Haliliye and Hamidiye in Siverek (right).

Subsequently, cul-de-sacs, which create private spaces towards the interior of the neighbourhood by differentiating from all roads, are shown in the plan (Figure 13, left). These street plans, which are shown in two consecutive neighbourhoods, give ideas about the organization of the neighbourhood. The situation of cul-de-sacs branching from roads and bending in their own direction was tried to be shown in the neighbourhood plan (Figure 13, middle). It is shown in the neighbourhood plan where we see the direction in which the cul-de-sac and the road that the street connects to continue, and we try to see how the street and the dead-end street intersect (Figure 13, right).

Figure 13. Cul-de-sacs of Haliliye and Hamidiye in Siverek (left). Twist plan of cul-de-sacs (middle). Cul-de-sac and street intersection plan (right).

In the neighbourhood plans where cul-de-sacs are shown and their connection to other streets is tried to be shown, it is aimed to explain how cul-de-sacs interact within the texture. (Figure 14) tries to make the intersection of the cul-de-sac with the road to which the street connects visible. The intersection angles of these streets can be obtained from here. Intersection angles constitute one of the rules of morphology in this study. How this rule is obtained and how it is converted into data is explained below.

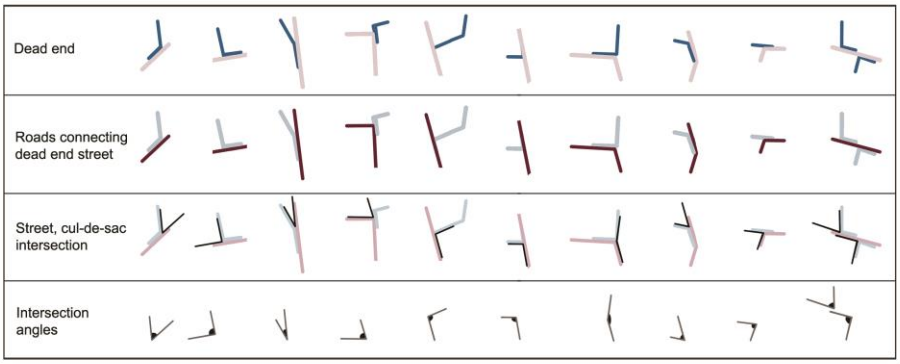


Figure 14. Intersection angles.

First of all, the neighbourhood boundary is determined and the resulting street typologies are placed. The width and length of the streets were organized as changeable. The connection angle of the streets, whether they are dead ends or not were placed in the circuit. As changes are made in the values in the circuit, changes in the texture formed within the determined boundaries are realized. With the change of values, the circuit results in textures with appropriate connections. As can be seen in Figure 15, as the parameter values of the circuit are changed in the specified area, different formations and different textures emerge. The goal of this study was realized and the project was found strong in this context.

Figure 15. New neighborhood pattern.

In the resulting street and connection plans, neighbourhood proposals were formed with the placement of residences. In the neighbourhoods formed, houses with courtyards or rectangular flat houses can be placed according to the preference. These two types of dwellings and the dwellings that diversify and increase in size within themselves take their place in the neighbourhood texture. As in Figure 16, different types of houses were placed on the street network plan created from the program. The gaps formed according to the angle of the streets are defined as squares.

Figure 16. Placing housing units within the new pattern.

The findings from the data processing, literature research, and experimental application of generative systems will be discussed in detail to highlight the strengths and limitations of this approach. The discussion will also address any challenges encountered during the implementation of the generative systems, potential areas of improvement, and recommendations for future research and practical applications. The overall goal is to provide valuable knowledge that can inform urban designers and planners in their efforts to create functional, aesthetically pleasing, and contextually appropriate neighborhoods.

5. Discussion and Conclusion

In this part, we will discuss the data processing from the field, the findings from the literature research, the selection of appropriate tools, and how the experiments conducted were connected to the results.

In this part, we will discuss the data processing from the field, the findings from the literature research, the selection of appropriate tools, and how the experiments conducted were connected to the results.

The creation of the Grasshopper circuit with reference to a local point is seen as the most unique part of the project. This circuit can be used in neighbourhood organizations to be created at the desired point. The neighbourhood data to be created can be processed into the circuit and products can be obtained by selecting from the typologies determined. Its use in every defined land reveals the strongest aspect of the project.

It is necessary to make a selection among the final products and make an evaluation on this selected final product. In this respect, it is determined as a weakness that the project lives within itself.

The digital integrity of the project that touches traditional places is considered important. The desire to discuss the concept of semi-public space in different interfaces enriched the project.

The study demonstrates how these generative systems could effectively generate street networks and cul-de-sacs in the context of new neighbourhood formations. By implementing the grammar rules and taking into account the unique characteristics of Haliliye and Hamidiye neighbourhoods, the study sought to illustrate the potential applications of generative systems in urban design and planning. The study contributes valuable insights into the potential use of generative systems in urban morphology and neighbourhood design, emphasizing the importance of considering unique urban contexts and characteristics when employing such computational tools.

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ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML) IN PRACTICE

A comprehensive investigation into the utilization of generative artificial intelligence (AI) and machine learning (ML) in architectural practice

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Abstract: This study offers a comprehensive investigation into the utilization of artificial intelligence (AI) and machine learning (ML) technologies within architectural practices. Since the introduction of computer-aided design (CAD), technology has had a significant impact on the way architects conduct their work. This study explores the potential of AI/ML in actual architectural workflows, with a particular emphasis on the capacity of deep neural networks to assist in the design process.The outcome will help to develop a clearer picture of the opportunities and barriers associated with AI for architects; they will also inform the prioritization of focus for future development of this technology in architectural practice, as well as identifying the specific tasks and project phases in which ML could play a role.

This research reviewed literature to explore various approaches for applying AI/ML technologies within the field of architecture. Also , complemented by a number of interviews to investigate the ways in which participants are currently using AI/ML in their work, framing the current feedback and the future potential of AI/ML technologies in architecture. The data collection methods adopted involved semi-structured one-on-one interviews with professionals from multi-regional architecture firms and AI developers. The architects interviewed exhibited diverse ways of benefiting from AI/ML technology, with varying approaches and some common trends. The findings demonstrate that AI has played a pivotal role in expediting the design process and enhancing visualization within the field. However, it has also raised concerns, particularly in the realm of privacy.

ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML) IN PRACTICE

Keywords: *Generative Artificial Intelligence (AI), Machine Learning (ML), deep neural networks, Architectural Workflows, Architects, Architectural Practice*

ملخص. تقدم هذه الدراسة تحقيقًا شاملاً في استخدام تقنيات الذكاء الاصطناعي (AI) والتعلم الآلي (ML) في الممارسات المعمارية. منذ إدخال التصميم بمساعدة الكمبيوتر (CAD)، كان للتكنولوجيا تأثير كبير على الطريقة التي يدير بها المهندسون المعماريون أعمالهم. تستكشف هذه الدراسة إمكانات الذكاء الاصطناعي/التعلم الآلي في سير العمل المعماري الفعلي، مع التركيز بشكل خاص على قدرة الشبكات العصبية العميقة للمساعدة في عملية التصميم. وستساعد النتيجة في تطوير صورة أوضح للفرص والعوائق المرتبطة بالذكاء الاصطناعي المهندسين المعماريين؛ سيقومون أيضًا بإبلاغ تحديد أولويات التركيز على التطوير المستقبلي لهذه التكنولوجيا في الممارسة المعمارية، بالإضافة إلى تحديد المهام المحددة ومراحل المشروع التي يمكن أن يلعب فيها تعلم الآلة دورًا. وقد قام هذا البحث بمراجعة الأدبيات لاستكشاف الأساليب المختلفة لتطبيق تقنيات الذكاء الاصطناعي/التعلم الآلي في مجال الهندسة المعمارية. بالإضافة إلى ذلك، يتم استكماله بعدد من المقابلات للتحقيق في الطرق التي يستخدم بها المشاركون حاليًا الذكاء الاصطناعي/التعلم الآلي في عملهم، وتأطير التعليقات الحالية والإمكانات المستقبلية لتقنيات الذكاء الاصطناعي/التعلم الآلي في الهندسة المعمارية. تضمنت أساليب جمع البيانات المعتمدة مقابلات فردية شبه منظمة مع متخصصين من شركات الهندسة المعمارية متعددة المناطق ومطوري الذكاء الاصطناعي. عرض المهندسون المعماريون الذين تمت مقابلتهم طرقًا متنوعة للاستفادة من تقنية الذكاء الاصطناعي/التعلم الآلي، مع اتباع أساليب مختلفة وبعض الاتجاهات المشتركة. توضح النتائج أن الذكاء الاصطناعي لعب دورًا محوريًا في تسريع عملية التصميم وتعزيز التصور داخل هذا المجال. ومع ذلك، فقد أثار أيضًا مخاوف، خاصة في مجال الخصوصية.

الكلمات المفتاحية: *الذكاء الاصطناعى التوليدى، التعلم الآلى، الشبكات العصبية العميقة، مسارات العمل المعمارية، المعماريون، ممارسة المهنة المعمارية.*

1. Introduction

Artificial intelligence and machine learning technologies have evolved significantly in many fields in recent years, including in architecture. While the exact definition is still contested, the term ‘artificial intelligence’ often refers to making a machine intelligent, with the ability to solve problems either by simulating or observing human methods (McCarthy, 2004). This study aims to offer a comprehensive investigation into the utilization and challenge of artificial intelligence (AI) and machine learning (ML) technologies within architectural practices. It explores the potential of AI/ML in routine architectural workflows, with a particular emphasis on the capacity of deep neural networks to generate drawings and assist in the design process. To do so, this paper investigates two interrelated threads. The first of these provides an overview of significant literature on the development of AI/ML technologies in architecture. It situates AI/ML technologies on a historical lineage of the adoption of digital technologies in architecture in order to speculate on their potential influence on the way we practice architecture. The second thread involves an in-field study of the actual application of AI/ML technologies in architecture firms. This includes a series of semi-structured interviews with different architectures and AI developers to map and reflect upon the current and potential use of AI/ML technologies within architectural firms. In bringing these threads together, the research aims to develop a clearer picture of the opportunities and barriers associated with AI for architects. The paper concludes by identifying possible tasks and project phases which AI/ML could support, and by speculating on the future trajectory of the development of AI technologies, both for architects and for the profession of architecture as a whole.

2. Method

The methodology for the research includes review of the literature exploring approaches to applying AI/ML technologies in architecture and a series of semi-structured interviews. While literature on AI/ML and architecture can be traced back to the early 2000s, the primary focus in this paper is on literature published between 2018 and 2023, as the peak evolution of generative AI technology started after the introduction and development of generative adversarial networks (GANs) in 2014 (Goodfellow et al., 2014). Sources were identified and selected using a systematic method to ensure a comprehensive and diverse view of the topic was generated. The main criteria for the selection process was that studies had clearly defined ways of using ML or deep learning (DL) models within the scope of work and services of architects in practice. Preference was given to literature that applied the model in the design phase and which addressed architectural tasks.

The literature review is complemented by a series of semi-structured interviews with relevant experts on AI/ML technologies and architects who are applying them in their practice. Participants were selected based on their experience with AI/ML, as published in their web profiles or research papers. The selection included a number of multi-regional architecture enterprises and a variety of positions, from senior architects and building information modelling (BIM) coordinators to co-founders. The interviews aimed to investigate the ways in which participants are currently using AI/ML in their work, framing the current feedback and the future potential of AI/ML technologies in architecture. The conversations therefore focused primarily on the benefits and limitations of utilizing generative AI tools, as well as on the specific tasks and project phases in which AI/ML could play a useful role.

Once data had been collected, thematic analysis of the literature and the interviews was conducted to identify the key potentials and expectations of AI/ML in architecture and the barriers to their application. These were used to develop a holistic understanding of the potential of AI/ML technologies and how they will influence architectural practices. The analysis of the literature review employed the four categories proposed by architect Phillip Bernstein in his book *Machine Learning: Architecture in the Age of Artificial Intelligence* (2022) to assess the capabilities of AI/ML within the field of architecture. The four categories will be present on the section 1.3.

3. PART 1: Literature Review

3.1 ARTIFICIAL INTELLIGENCE (AI) & MACHINE LEARNING (ML): A BRIEF HISTORY

AI/ML are not new technologies: they date back to the 1950s (Steenson, 2017). However, since that time, there have been significant developments, focusing on creating and advancing big data technology and presenting it in a new way. This process has particularly accelerated since 2015, when the DeepMind technology (Silver et al., 2017) was first developed, and design professions, including architects, are now encountering new kinds of digital tools - not simply tools for drawing and making but tools designed to think (Carpo, 2017). As result, architectural practice is encountering a shift in its ways of conception and production, raising questions about the potential of these applications, the risks to creativity, changes to the role of the architect, and broader 'revolutionary' changes to the profession.

Research exploring AI/ML has also experienced significant growth in recent years, particularly since 2015. According to Castro Pena et al. (2021) the number of publications investigating AI/ML in the field of architecture rose by 50% from 1995 to 2019, with a remarkable 85% growth in the period between 2015 and 2019. This can be attributed to several factors: the involvement of The Internet of Things (IoT) technologies, and the ability to collect and store vast amounts of data; the development and validation of more advanced ML algorithms, such as deep neural networks; and improvements in the efficiency of manufacturing Graphic Processing Units and Tensor Processing Units and reductions in their costs (Blanco et al., 2018; Darko et al., 2020; Hong et al., 2020).

While AI/ML have become an essential part of multiple disciplines today, architecture appears to be having a hard time coming to terms with them. Despite the growing research efforts exploring AI/ML, the profession is often cautious in terms of adopting new technologies, and, as Khean et al. (2018, p. 95) argue, the field of architecture is "objectively one of the slowest industries to integrate with machine learning." Aligned with the findings of the

McKinsey report (Chui et al., 2018), the adoption of AI solutions is notably lower in the engineering and construction fields compared to other industries.

3.2 ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML): DEFINITIONS

The term ‘artificial intelligence’ has been defined in a variety of ways over time, but there is still no universally accepted definition (Mikalef and Gupta, 2021). One of the earliest definitions was given by John McCarthy (2004), and its main point was to explain the science of AI: “It is the science and engineering of making intelligent machines, especially intelligent computer programs.” However, AI has now become a top technological priority for organizations, and many governments are working to establish regulations to manage it, with new definitions emerging as the technologies evolve. For example, in 2021, the UK developed a new National Strategy for Artificial Intelligence, which defines AI in the following terms: “Machines that perform tasks normally performed by human intelligence, especially when the machines learn from data how to do those tasks” (Department for Science, 2021).

The incorporation of ML in the UK Government definition adds a new element to the earlier definitions; however, there is sometimes confusion between the terms “artificial intelligence” and “machine learning”. In simple terms, ML is a subfield of AI which “involves tools that allow computers to learn from data” (Corea 2019, p. 26), and, while some AI systems use ML methods to achieve competence, others do not.

Deep learning is a type of ML that allows computational models that are composed of multiple processing layers to learn representations or to generate data with multiple levels of abstraction without any human input (LeCun et al. 2015). The emergence of deep neural networks (DNNs) in the field of ML has revolutionized the automation of tasks involving qualitative patterns recognition. Indeed, these deep discriminative models have performed so well that they have been able to outperform human experts on classification tasks as varied as image and sound recognition. One deep generative model that has demonstrated impressive results in the generation of 2-D and 3-D designs in particular is the generative adversarial network (GAN) (Goodfellow et al., 2014), and this has significant potential to enhance architectural workflows.

3.3 AI/ML IN ARCHITECTURE

The literature on the potential application of AI/ML in architecture can be traced back to the early 2000s. However, early studies focused primarily on computational design and computer science areas and mostly categorized and examined applications according to the neural network types or ML modes. It was not until the end of the second decade of the new millennium that a renewed interest in AI and architecture practitioners led to the topic becoming a significant area of research.

The purpose of this paper is to evaluate the potential of AI/ML technology during the design phase of a project from the practitioner's perspective. Examining AI/ML technology from this standpoint will assist in framing its capabilities and redefining its place in architecture practice, and a number of studies are relevant in this context. For example, a study by Tamke, Nicholas and Zwierzycki (2018) proposed that new architectural design practices would be based on ML, so architects and engineers would need to find new models to leverage data more effectively. A year later, a paper by Wanyu He and Xiado Yang (2019) explored AI design as a new approach in order to build a scenario of the possibility and application of AI design in the future. More recently, Castro Pena et al. (2021) aimed to review and categorize the applications of AI in the conceptual design stage. In their research, they examined 75 studies related to this topic, classifying them based on different areas of conceptual design and providing insights into how AI can be utilized effectively in architectural practices, thereby offering valuable guidance for research projects that apply AI to architecture.

More recently, a key reference for the theoretical implications of applying AI/ML in architecture was provided by architect and technologist Philip Bernstein in his book *Machine Learning: Architecture in the Age of Artificial Intelligence*. The discussion and examination focus on three aspects: the potential changes in architectural processes with the integration of AI/ML, the impact on relationships with built environment delivery systems, and the opportunities to refactor and enhance architectural outcomes. Bernstein points out that these will require significant changes in the field, commenting that, *'The advent of machine learning-based AI systems demands that our industry does not just share toys, but builds a new sandbox in which to play with them'* (p. 130).

In this book, Bernstein classifies the capability of AI/ML in architecture according to four criteria: Evaluation, Simulation, Generation, and Understanding (Bernstein, 2022). The present study also uses these categories to assess the capabilities of the applications of AI/ML discussed in this paper but with a slight difference. As studies using AI/ML for evaluation or understanding share similar features, this study combines the evaluation and understanding of AI capabilities into one classification, leading to three classifications as follows:

- **Evaluation and Understanding:** The system is capable of defining information, understanding the implications, and deploying it;

- **Simulation and optimization:** Using information to approximate similar circumstances or optimizing the simulation in a different context.
- **Creation and Generation:** Capable of creating new ideas, or generation from multiple different datasets, which may include image, text, video, or voice format etc.

The following section discusses the literature that focuses on the application of AL/ML in architectural practice according to these categories, providing three examples of previous studies that aimed to use this aspect of AI/ ML's capabilities at a particular stage of a project are provided for each category.

3.3.1 Evaluation and Understanding

The capability for evaluation and understanding are best presented in a study by Uzun & Çolakoğlu (2019), which trained a convolutional neural network (CNN) to recognize architectural drawings. By analyzing pixel-based data, the CNN was able to differentiate between a section cut drawing and a plan cut drawing, and it demonstrated an 80% accuracy in algorithmically classifying and evaluating plan and section drawings.

A study by Yoshimura, Cai, Wang and Ratti (2019) also examined the capability of CNNs to classify architectural designs. These were utilized to identify and cluster 34 different architectural projects in the modern and contemporary era, with the aim of helping to understand how state-of-the-art application of AI aesthetics could enhance the work of architectural historians and theorists.

In addition, Wu & Liu (2019) investigated how to apply CNNs to facilitate an important step of the architectural design process, namely determining the appropriate building site. Their experimental results demonstrated that the application of a CNN could assist in determining the most appropriate locations for different types of studios by analyzing 'the architectural site'.

3.3.2 Simulation and Optimization

AI/ML have been widely employed in simulating the performance of buildings, and many studies using AI for simulation and optimization have focused on accelerating previous simulation methods while achieving more accurate results. The AR+D department at Foster and partners provide a good example; they explored the potential of using ML, specifically CNNs, to run real-time simulations for computing the spatial and visual connectivity of a given floor plan (Tarabishy et al., 2019). The study's outcomes indicate that CNNs can significantly accelerate computation times and reduce the resources required to generate results from the analysis.

In addition, Sebestyen and Tyc (2020) investigated the application of a CNN to assist architects with environmental analysis in the design process. They developed a workflow generating an ML model capable of predicting solar radiation and sunlight hours analysis to a degree of accuracy that is suited for early-stage design.

On a similar theme, a study by Alammar et al. (2021) employed multiple ML models, including Artificial Neural Network (ANN) and Decision Tree (DT), as alternative approaches to assess the simulation of solar radiation intensity on the building envelope. Their results showed significant benefits in terms of time-saving during the solar radiation simulation process.

3.3.3 Creation and Generation

A novel study by As et al. (2018) employed various DL techniques, including GANs, to develop an alternative graph-based ML system which was capable of dealing with three-dimensional space. The system demonstrated the capability to train neural networks to evaluate and generate new conceptual designs using graph-processing, even for designs which were not present in the training set.

In a thesis submitted to Harvard in May 2019, Chaillou explored the potential of AI/ML to design floor plans and, potentially, entire buildings (Chaillou, 2020). His use of GANs to generate alternatives layouts for a floor plan has now been widely adopted, and there are now many software companies on the market utilizing GANs to benefit from this capability.

Another study conducted by Newton (2019) also used a GAN to generate architectural plans. In this case, a GAN was trained on a selection of plans by Le Corbusier.

3.4 THE USE OF GENERATIVE AI SOFTWARE IN ARCHITECTURAL PRACTICE

There has been an explosive revolution in the application of AI generation. On a daily basis, we are witnessing the emergence of new tools and program versions based on generative DL technologies, such as DALL-E 2, Midjourney, and ChatGPT, and these emerging applications underline the potential of AI/ML technology at the present time (Peres et al., 2023). Such applications are not just limited to conventional work domains but encompass the potential of creative and fine arts, including visual arts, architecture, music, and film (Oksanen et al., 2023). During the interviews with practicing architects conducted for this study, the majority reported using one or more of these applications in their work; however, some have become reliant on these tools on a permanent and daily basis. This section identifies and describes the two AI generative models (text-to-text and text-to-image) which were most commonly used by the research participants; it also considers the state-of-the-art of generative AI tools currently being used by professional architects.

3.4.1 Text-to-Text AI Generation

ChatGPT is an application of text-to-text generative AI (Ray, 2023), which was developed by OpenAI, an AI research laboratory and company (Mohamadi et al., 2023). ChatGPT is based on an unsupervised language learning model, which generates text in response to user input on a chat platform, and it is capable of completing multiple and diverse sets of tasks, including assisting with writing, coding, and providing a fast, efficient way to find information (Cao et al., 2023). It can generate responses in multiple languages and across a multitude of disciplines (Borji, 2023). Moreover, while ChatGPT is currently the best-known example of text-to-text generative AI, the trend of harnessing its potential to assist with tasks through interactive chatbots is witnessing an increase. Some of these specialize in a specific field or type of task, for example, Woebot is designed for mental health support, LawBot is for the legal field, and GitHub Copilot is for coding and programming (Cao et al., 2023), while others are more general, for example Bard by Google and Microsoft. The topic of engagement with AI chat was an intriguing feature of the interviews, with some of the participating architects discussing cases related to their daily tasks and fields of work, while others considered wider applications for the technology.

3.4.2 Text-to-Image AI Generation

Tools for generating images have made significant advances since the proposal of GANs in 2014 (Goodfellow et al., 2014), something now regarded as a milestone due to its widespread application and impressive performance (Cao et al., 2023). A year later, in 2015, Google introduced ‘Deep Dream’, which enhanced the output of neural networks; this provided a new approach to remixing visual concepts and demonstrated the potential of neural networks as a tool for artists (Mordvintsev et al., 2015). Moreover, in 2019, NVIDIA introduced Style GAN, which enabled the artistic style of one image to be transferred to another and represented a paradigm shift in the capabilities of GAN technology (Karras et al., 2019). Today’s text-to-image generator tools, such as Midjourney, DALL-E 2, and Stable Diffusion, are based on DL models and can generate images in response to textual inputs from users on chat-based platforms (Ghosh and Fossas, 2022; Oppenlaender, 2022). With their capacity to produce highly realistic images and their easy-to-use interfaces, these tools have now become broadly applicable in the context of architecture, and the discussions in this study suggest that they have considerable potential in the field, with many reasons to encourage architects to adopt them.

4. PART 2: Interviews

4.1 THE INTERVIEWEES

Parallel to the selective literature review, we conducted interviews with architects specializing in state-of-the-art technology and AI/ML and with software developers to gain insights into their application of AI/ML. The architects were selected based on specific criteria, including their experience with digital tools, such as BIM, CAD, and coding, in their professional careers. Care was taken to ensure they held different positions, including regional design director, technology manager, and engineering/computational design professional. None of them worked for the same company, a deliberate choice made in order to gather a diverse range of ideas and perspectives.

TABLE 01: Demographic data of the participants

Name	Position/Specialism	Interview Duration	Region
P01	Civil Engineering /Computational Design	58 mins	UK
P02	Architect/Regional Design Director	58 mins	U.A.E
P03	Architect/ Leader in Design Technology	43 mins	USA
P04	Architect/Computer Science	30 mints	Germany
P05	Architect/ Design	30 mints	UK
P06	Architect/ BIM and Design Technology	45 mins	USA

4.2 THE INTERVIEW QUESTIONS (STRUCTURE)

A semi-structured interview format was adopted, which used a set of open-ended questions but was flexible enough to allow additional questions to be asked based on the interviewees' responses as the conversation developed (Lucas, 2016). This type of interview allows for a more in-depth exploration of topics, especially when they are relatively new. In these interviews, the participants' responses were direct, specific, and concise regarding the topics mentioned above. This paper includes a brief overview of their responses, with a focus on conveying their views on the current and potential benefits of using AI models to generate images or texts and the barriers to their use.The interviews were conducted to achieve the following three main objectives, which also align with the aim of the research:

1.Exploring the potential of AI/ML tools to enhance architectural practices;

2.Identifying the challenges and barriers interviewees face in adopting and utilizing AI/ML tools in their practice;

3.Observing the future of the practice in light of the advances in AI/ML technology.

The interview questions were structured into four main sections, with an introductory section, then a section for each objective. A brief description of each section is provided below, and a list of sample questions can be found in the appendix.

1.General overview: establishing general information about the architectural firm;

2.Potential, Benefits, and Opportunities: focuses on understanding the potential of AI/ML as tools for architects.

3.Challenges, Barriers, and Difficulties: This section discusses the barriers to the adoption of AI/ML (any of the models used) within the interviewees' practices and the limitations of the technology.

4.Future: This part examines two aspects: a) the future of architecture as a career, and of the architect as a professional, and b) the architecture tasks that will change through the use of AI/ML.

4.3 ANALYSIS:

Diverse viewpoints emerged among the interviewees regarding the potential of AI/ML technology , the obstacles to its adoption, and its future applications. To reach the result, the gathered data were categorized into three main groups based on the type of AI generator model utilized by the participants: Text-to-Image, Text-to-Text, and a broader category encompassing AI/ML technology in general. Following this, the interview transcripts underwent a detailed examination and classification into four subclasses: Potential, Challenges, Future, and General information.

Identification of these relevant sections or sentences involved a comprehensive analysis of the context surrounding specific keywords such as 'challenges,' 'barriers,' 'difficulties,' 'potential,' 'benefits,' and 'opportunities.' These keywords were derived from the research objectives and designed to align with the primary research aim.

Lastly, the data underwent further analysis and were categorized into two main sections: Potential and Barriers. A summarized overview of the opportunities and obstacles associated with Text-to-Image AI generators and Text-to-Text AI generators is presented in Table 2."

4.4 A SUMMARY OF THE MAIN POINTS DURING THE INTERVIEWS

The following sections provide highlights from the interview conversations about text-to-image generative AI and then about text-to-text models. While some participants expressed strong views, it was evident that others were unclear in their perspectives; however, common ideas and concerns emerged.

4.4.1 Text-to-Image Generative AI models

Communication during the early design stage: An advantage of Midjourney was the ability to process and generate large amounts of images that help make the communication during the early design stage smoother, enabling explanations and discussions to be more visual rather than verbal. In other words, the discussions will involve more architectural language graphics than words. The second participant (P02) reported that:

“We use it in our studio almost like a Pinterest board, the process we used to do”.

A Pinterest board, a physical or digital collection of various visuals, has a crucial role in the initial stages of any project, providing the team with inspiration, shaping ideas, and generating discussion of further developments. Generating these manually was a time-consuming process; however, AI tools can generate a wide range of visually appealing images much more quickly, significantly enhancing this stage of the process. The fifth participant, P05, made a similar point:

“AI is a personalized Pinterest. If you think about this, it's kind of your own personal mood board that you create through your own vision…”.

The first participant, P01, also agreed that using Midjourney to generate images was helpful in facilitating communication. In his view:

“I was able to use machine learning for very quickly sketching out ideas to communicate what I meant, without me having to describe it.”

Visualization and Exploration: opening up the boundaries of creativity and exploring new ideas. Participants agreed that Midjourney allows them to push the boundaries of creativity and generate unexpected ideas. For example, P02 explained that:

“If you’re looking for a reference image to show your colleagues, [using Midjourney] is good to create things that you want to exchange with others, or even see them for yourself…”

Midjourney, DALL-E, and other AI image generator tools open up new possibilities for imagination, visualization, and expands their expectations and ways of thinking about project concepts. GANs have the remarkable ability to create images for ideas that have never existed before. They can also generate entirely novel images of concepts by blending and synthesizing counter elements from difference sources, leading to products and imaginative ideas that were previously inconceivable.

Accelerate the design process: There was consensus among the participants that one of the most valuable potentials of AI image generation is to accelerate the design process. Specifically, GANs can generate and render large quantities and high-resolution images in a short period of time, significantly accelerating the exploration of different design options to identify the most promising ones. This is a key advantage for professionals because saving time can reduce the cost of a project. The fifth participant (P05) acknowledged that tasks which previously required several weeks, or the efforts of a whole team, could now be completed within hours by one person and an AI tool, such as Midjourney:

"Probably it was 3 - 4 weeks of work modelling, rendering, reviewing... [However, with Midjourney,] in 5 hours I managed to create more."

The ability to generate a large number of images and information is most beneficial during the brainstorming and analysis phase of the design process, providing designers with visual stimuli and ideas that help to generate refined final design solutions.

The majority of the participants could see that there is huge potential and numerous opportunities to involve AI generators in architectural work. However, there are challenges and barriers. Some of these pertain to specific models of AI generators or software types, while others are general and can be considered as barriers to the integration of any AI/ML technology. Some of the issues the interviewees identified were:

Lack of privacy: The second participant (P02) identified a major issue with Midjourney. The tool is designed to learn from user interactions, and it is similar to an open chat, meaning users can view each other's work. As P02 noted, this raises data privacy issues:

"There is a certain challenge with using it at work. One of them, when you're in the public forum, everyone can see your prompts and your images".

Professionals in many countries are legally obliged to protect confidential information, and there are concerns that platforms such as Midjourney might not comply with privacy regulations due to their open nature.

Intellectual property rights: another challenge related to privacy and rights associated with Midjourney may also extend to any AI/ML models capable of generating data text, images, or voice. Both P02 and P05, as well as other interviewees, expressed concerns that generative AI technology could infringe upon intellectual property rights and copyright law. P02 recognized this problem and said that it acts as a deterrent to using the software at work:

"I don't use (Midjourney) fully or directly for work because I am still not clear about the ownership of intellectual property (IP)"

Interface and control: the Midjourney interface is very similar to chat or game forums, so it does not look like a regular software program. The Midjourney and DALL-E interfaces also use minimized icons or toolbars, and this can make them difficult to control. In addition, the neural networks Midjourney is based on have some difficulty in controlling or understanding the behaviours of neural nets, so the final outcomes may not be what was expected when the prompt was entered.

4.4.2 Text-to-Text Generative AI Models

The second most commonly used model by participants is the text-to-text generative AI model, ChatGPT. This model cannot be considered as an art or architectural tool like Midjourney, but throughout the interviews, the quality of ChatGPT's responses was praised, and the ways participants use it shows how useful they find it. The benefits they identified included:

Learn and develop new skills: ChatGPT could help architects learn and develop new professional skills. It can be difficult to keep learning new things, but ChatGPT could help with skills such as coding and programming, which have become necessary skills for architects since the development of visualising programs, such as Grasshopper and Dynamo. P06 commented:

"I've been looking at it as kind of integrating ChatGPT or an AI opportunity inside things like Dynamo and Grasshopper".

Aids with subtasks: ChatGPT could help architects to perform or enhance the quality of tasks that are not within the main core of the architect's workflow, but which are important for facilitating work in firms, for example, report writing and summarising written materials. P01 thinks that ChatGPT can be a good option to assist architects in their writing:

"I think in terms of writing. You know, architects have to write as well, right, like they have to write about their designs, and also, they have to summarize…"

A Personal trainer: ChatGPT can be used for training and obtaining auxiliary information, a program, a skill, or even a choice of the best options. P03 commented that:

"If I don't know how to do something, and I can't find someone who does, this is more than just a Google search."

In light of these responses, we asked a text-to-text AI model (ChatGPT3) for a brief description of the ways it could assist architects. Much of its response aligned with the participants' thoughts, but it also considered other aspects:

"ChatGPT can assist architects in idea generation, problem-solving, design reviews, material and product suggestions, code and regulation compliance, collaboration and communication, research and knowledge gathering, conceptual visualization".

4.4.3 Other AI/ML Models:

Overall, gathering feedback from participants who tried both text-to-image and text-to-text AI models, as well other models, helped to analyse and understand the following about the overall technological capabilities of the AI/ML tools, and the challenges associated with them:

- There was agreement that AI/ML tools and related technology have the potential to be applied and utilized in all project phases and stages, from the initial concept to handing over a project. However, their capacity to be involved in the early design stages is most clear at the moment.
- AI/ML typically performs routine tasks at the moment. The participants were asked what type of tasks they thought AI/ML can be useful for at the moment and what type of tasks they believe it has the potential to fully automate in the future. Most of the answers referred to types of activities that involve patterns and repetitive action, and these tasks are well-suited for AI/ML capabilities to learn. However, some participants also mentioned creative tasks.
- Although the outcomes of AI/ML are satisfying, we still need the human eye. There is an agreement that AI/ML has the potential to handle and assist with a lot of tasks; however, the possibility of errors or faults should not be overlooked.
- Lastly, AI/ML can be modelled and trained for implementation in various fields. However, it can be quite complicated to programme and build a model from scratch, especially for architects who lack coding skills and other requirements for ML. Learning the necessary technical aspects of AI implementation can be challenging for architects, making this a potential barrier to adopting AI technology in their field.

TABLE 2: Potential of text-to-image and to text AI in architecture and barriers to its adoption

Text-to-Image AI Generators	
• Ability to process large amount of images to help make communication during the early design stage smoother. • Facilitating communication. • Opening up the boundaries of creativity and adding new ideas. • Accelerating the design process.	• There is some lack of clarity about intellectual property rights relating to the data sets used to train generative AI technology and the images it produces. • Lack of data privacy. • Interface and control.
Text-to-Text AI Generators	
• Could help architects learn and develop new skills. • Provides assistance for architects on subtasks. • Can be applied in all project phases.	• Coding and programming have now become necessary skills for architects.

5. Discussion

Architectural practice is undergoing a significant transformation that will reshape many of its aspects. Just as tools like CAD and BIM have become widely used, AI and ML will permeate many areas and affect a broad range of stakeholders. Indeed, the aspirations for AI/ML today resemble those about CAD in the early 1980s and BIM in the 2000s, and arguments about the benefits of utilizing AI in the early design phases are similar to those about CAD as Computer Aided Design or Computer Aided Drawing/Drafting in the 1980s and 1990s (Lawson 2006).

Currently, we are at the initial stages of this transformation. The increasing number of research and development programmes is clear evidence of the formidable potential that AI holds for architectural practice. However, levels of interaction and integration are not yet optimal when compared to other industries. There is still some pessimistic discourse around AI taking away jobs, and concerns about technological determinism: that it could lead to the ways architecture is practiced being determined according to the logic of technology rather than by architects themselves. However, the literature review demonstrated optimism about the benefits that AI/ML tools can bring to the architect. Part of this stems from a belief in the idea that technology, especially its generative capabilities, holds significant potential to integrate with architectural practice and will lead to a better future.

Overall, the feedback gathered from the interviewers and the literature can guide and shape our understanding of the potential and status of AI and how it will impact the future of architectural practices. The interviews have helped to clarify some of the uncertainty associated with the big noise currently happening around AI and architecture, and demonstrate that, in practice, people are not overly enthused about the potential of AI/ML. However, while their involvement was limited to generic types of text-to-image and programs that are not specifically designed for architectural purposes, they can see that these tools can be useful if applied in an intelligent way, and they are already having a positive effect on architectural workflows.

In addition, the utilization of AI may be a way for architects to regain their leading role in the building industry through a redefinition of their profession with a new set of digital tools. These tools are not limited to assisting with physical activities, such as drawing and modelling, but can also extend to cognitive and creative aspects. Alternatively, we might witness the emergence of a new generation of professional practices which are fully based on AI technology, where the architect's role will be as a supervisor of the system.

Neither of these scenarios can avoid acknowledging that datasets are the most valuable and crucial elements for engaging and implementing AI in the architecture and construction industry. Embracing the AI technology revolution fully relies on having comprehensive and relevant datasets in place. However, throughout our exploration, we have not encountered a definitive solution for efficiently circling, collecting, and setting-up data, from the initial design stage to all the subsequent stages of the building lifecycle.

6. Conclusions

In conclusion, this paper has demonstrated that AI/ML is already having a tangible impact on architectural practice, and its influence is expected to grow. One of the strengths of AI lies in its ability to support and create links between computer intelligence and architectural expertise, and blending AI capabilities into current practices can enhance architectural thinking and offer new avenues for design exploration and decision-making. As noted by Chaillou (2020) and Leach (2023), AI therefore has the potential to become a powerful tool to augment the intelligent processes of design and construction.

However, it is important to recognize that AI/ML is still in its early stages and, while it shows promise, there are still many areas that need improvement and development. Although the rapid advancements in AI technology recently foreshadow a more refined and efficient process in the coming years, it is difficult to say whether this will have a positive or negative impact on the profession, and many of the interview participants were unaware of the vast potential and possibilities of AI/ML technology at a large scale.

The findings of this study indicate that the future of the architectural profession will undoubtedly involve AI, and architects must be astute in embracing and leveraging this technology to their advantage. This will enable them to find new, innovative, and sustainable design solutions and to shape the future of their practice, providing an important opportunity to redefine their profession and their role within the building construction industry.

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ADVANCING 3D CONCRETE PRINTING FOR AFFORDABLE HOUSING: A SHAPE GRAMMAR-BASED APPROACH TO PRINT SPANNING ROOF STRUCTURES

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Abstract. 3D concrete printing (3DCP) technology is expected to address the construction industry's inefficiency, lack of skilled labor, and safety concerns, while tackling the housing shortage due to global population growth. Current applications in academia and industry have mainly focused on fabricating wall elements, which do not fulfill the potential of this technology to fully automate the construction process, including enclosures. In concrete construction, formwork is an essential part that fundamentally influences labor needs, quality, time, and cost. Many building components, such as walls, beams, columns, and prefabricated blocks, have been successfully printed without formwork using various additive manufacturing (AM) techniques for 3DCP. However, due to a 60-degree printing angle restriction when using a horizontal slicing technique and a corbelling printing method, to print spanning structures without formwork remains a challenge. Most state-of-the-art studies in 3DCP have focused on developing strategies to fabricate formwork, rather than developing new techniques for printing them without formwork. This research aims to leverage the power of shape grammar to overcome the challenges of printing spanning roof structures in 3DCP. By drawing inspiration from historical structures, we propose a multi-directional printing approach, integrating corbelling, radial, and inclined slicing techniques for toolpath design. Our objective is to establish shape grammar rules to break down enclosures into printable patches, design corresponding toolpaths using various slicing techniques, and validate the effectiveness of this approach by physically fabricating a prototype. To achieve this objective, an algorithm, incorporating shape grammar rules and numerical modelling software, to optimize the 3D concrete printing process for spanning roof structures was developed. Through this generative design system, designers can efficiently generate diverse and sustainable roof designs, specifically tailored for affordable housing solutions.

Keywords: *Shape Grammar, Parametric Design, Additive Manufacturing, 3DCP, Enclosures, Spanning roof structures.*

ملخص. من المتوقع أن تعالج تقنية الطباعة الخرسانية ثلاثية الأبعاد عدم كفاءة صناعة البناء، ونقص العمالة الماهرة، والمخاوف المتعلقة بالسلامة، مع معالجة نقص المساكن بسبب النمو السكاني العالمي. ركزت التطبيقات الحالية في الأوساط الأكاديمية والصناعية بشكل أساسي على تصنيع عناصر الجدران، والتي لا تحقق إمكانات هذه التكنولوجيا لأتمتة عملية البناء بالكامل، بما في ذلك العبوات. في البناء الخرساني، تعتبر القوالب جزءًا أساسيًا يؤثر بشكل أساسي على احتياجات العمالة والجودة والوقت والتكلفة. تمت طباعة العديد من مكونات البناء، مثل الجدران والعوارض والأعمدة والكتل الجاهزة، بنجاح بدون صب الخرسانة باستخدام تقنيات التصنيع الإضافي المختلفة للطباعة الخرسانية ثلاثية الأبعاد. ومع ذلك، نظرًا لقيود زاوية الطباعة البالغة 60 درجة عند استخدام تقنية التقطيع الأفقي وطريقة الطباعة المزخرفة، تظل طباعة الهياكل الممتدة دون صب الخرسانة يمثل تحديًا. ركزت معظم الدراسات الحديثة في برنامج الطباعة الخرسانية ثلاثية الأبعاد على تطوير استراتيجيات لتصنيع القوالب، بدلاً من تطوير تقنيات جديدة لطباعتها بدون القوالب. يهدف هذا البحث إلى الاستفادة من قوة قواعد الشكل للتغلب على تحديات طباعة هياكل السقف الممتدة في تقنيات الطباعة الخرسانية ثلاثية الأبعاد. من خلال استخلاص الإلهام من الهياكل التاريخية، نقترح نهج طباعة متعدد الاتجاهات، ودمج تقنيات التقطيع والشعاعي والمائل لتصميم مسار الأدوات. هدفنا هو إنشاء قواعد نحوية للأشكال لتقسيم المرفقات إلى تصحيحات قابلة للطباعة، وتصميم مسارات الأدوات المقابلة باستخدام تقنيات التقطيع المختلفة، والتحقق من فعالية هذا النهج من خلال تصنيع نموذج أولي فعليًا. ولتحقيق هذا الهدف، تم تطوير خوارزمية تتضمن القواعد النحوية للأشكال وبرامج النمذجة العددية لتحسين عملية الطباعة الخرسانية ثلاثية الأبعاد لهياكل الأسطح الممتدة. من خلال نظام التصميم التوليدي هذا، يمكن للمصممين إنشاء تصميمات أسقف متنوعة ومستدامة بكفاءة، ومصممة خصيصًا لحلول الإسكان بأسعار معقولة.

الكلمات المفتاحية: *قواعد الشكل، التصميم البارامترى، التصنيع الرقمى بالإضافة، الطباعة الخرسانية ثلاثية الأبعاد، الحدود الفراغية، هياكل الأسقف الممتدة.*

1. Introduction

The construction industry is facing challenges such as a lack of efficiency, skilled labor, and safety concerns. Additionally, the increasing world population has resulted in a shortage of affordable housing. According to statistics, inadequate housing and substandard living conditions affect 1.8 billion individuals living in informal settlements. Furthermore, an estimated 15 million people are subject to forced eviction annually, and 150 million people worldwide are experiencing homelessness (McRae, 2022). To address the shortage of affordable housing, there is a need to devise new and innovative construction methods that can overcome the inefficiencies of traditional construction practices while also reducing their impact on the environment. 3DCP has the potential to be a game-changer in the construction industry, providing affordable and rapid housing solutions and opening new possibilities for creative and innovative housing designs.

Compared to conventional construction methods, 3D printing allows designers to create complex shapes with higher functionality, efficiency, and customization in less time while significantly reducing construction waste. Additionally, it reduces the construction cost and waste. According to the

U.S. Department of Energy, AM on average, uses 50% less energy and saves up to 90% on materials expenses compared to conventional construction (Additive Manufacturing: Building the Future, 2017). Different AM techniques used for 3DCP have already successfully printed many building components without formwork except enclosures because of the current limitation of 3DCP. The corbeling technique, which involves printing with a vertical nozzle, limits overhangs to a minimum of 60° as shown in Figure 1(a) (Duarte et al., 2021). Therefore, the shape needs to keep the maximum overhang angle within 60° and have a pointed arch (Figure 1b) to be printed without formwork. The corbelling slicing technique involves intersecting the 3D geometry with a horizontal plane, starting from the bottom, and repeating this process at certain intervals to slice the entire part.

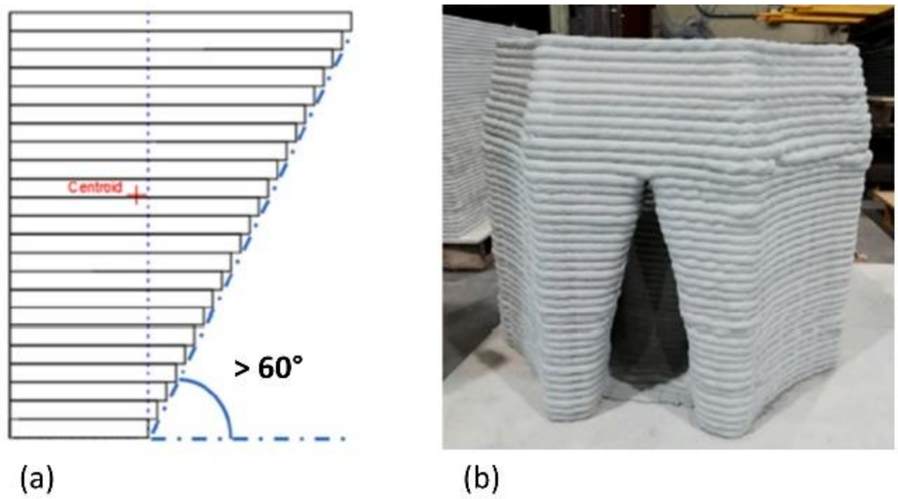


Figure 1: Overhang angle of 3DCP; (a) front view of layer deposition with a maximum overhang of 60°, and (b) self-supporting pointed arch (Duarte et al., 2021).

To prepare the models for 3D printing, several essential steps are involved. Two of the most crucial steps are creation of the 3D model and generating the toolpath that the 3D printer will follow during printing. To accomplish these tasks effectively, it is beneficial to explore two complementary methods: shape generation and shape decomposition. The primary focus of the first method lies in the digital generation of shapes during the design process. It involves creating or assembling the desired shapes using various design techniques. On the other hand, the second method, revolves around dividing the designed shapes into parts during the toolpath generation (Ashrafi et al., 2022). This segmentation allows the 3D printer to physically recreate and assemble the shapes layer by layer during the printing process. By employing these two methods together, designers can efficiently translate their digital concepts into tangible 3D printed objects.

Computation-based design, using generative algorithms, reduces time and cost by rapidly generating and evaluating multiple iterations. Generative design (GD) employs algorithmic or rule-based processes for diverse and complex solutions, encompassing various approaches like evolutionary methods, shape grammars, and cellular automata (Caetano et al., 2020). Shape grammar stands out as a powerful method for generating intricate 3D shapes through predefined rules and constraints. Designers benefit from its versatility, accessing a wide range of design options and creating unique and diverse designs. In the context of 3D concrete printing, shape grammar is particularly advantageous, as it facilitates the generation of shapes optimized for this specific fabrication technique.

This research aims to develop a generative design system for 3DCP of spanning roof structures using shape grammar rules. The primary objective is to develop shape grammar rules of enclosed shapes based on historical examples and convert them into a parametric algorithm. These rules will be designed considering the constraints and limitations of 3DCP. The proposed system will allow designers to generate complex roof structures using a set of predefined rules, which will result in efficient and cost-effective design solutions. The study will explore the potential of shape grammar rules in creating diverse and sustainable structures using 3DCP technology for affordable housing. This paper is part of a larger research project that includes structural simulation, optimization, and the use of shape grammar for shape generation. While this paper provides a brief overview of the shape grammar component, future work will delve into further detail on the shape grammar rules and describe the structural simulation and optimization methods used in the study.

2. Background

2.1. HISTORICAL STRUCTURES SUITABLE FOR 3DCP

In the history of architecture, there are numerous precedents of self-standing spanning structures (Figure 2). In addition, spanning structures provide an excellent structural system for construction materials (Curth et al., 2021). The main types of spanning structures found in historical precedents can be classified considering boundary conditions and shapes, such as arches, vaults, domes, and multi-curvature shells, as shown in Figure 3.

Figure 2: Historical spanning structures; (a) The Colosseum, Rome; (b) New Gourna Village by Hassan Fathy, Egypt; (c) The Basilica di Santa Maria del Fiore, Florence; (d) Los Manantiales, The Flower by Felix Candela, Mexico City.

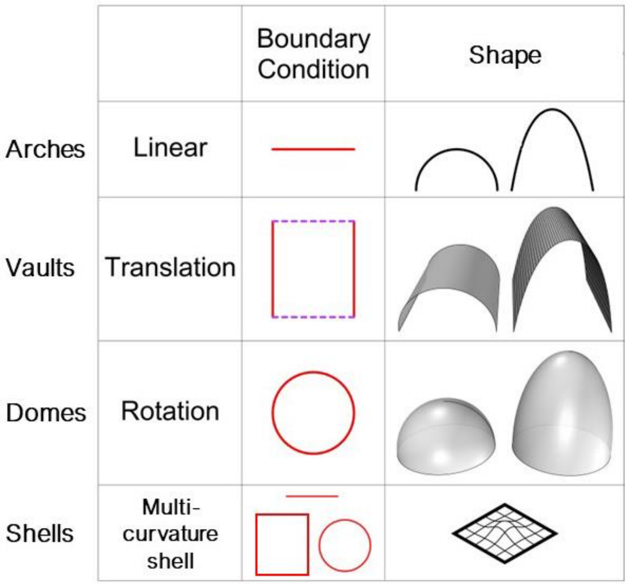


Figure 3: The main type of spanning structure found in historical precedents.

2.2. SLICING TECHNIQUES FOUND FROM HISTORICAL EXAMPLES

Construction techniques of spanning structures in history provide numerous fabrication ideas without using formwork, especially stone, adobe, and masonry constructions. The structures shown in Figure 4a, Figure 4b, and Figure 4c, respectively, seven arches made of stone, an adobe dome, and

Nubian vaults, present examples of the construction of spanning structures that work under compression.

Figure 4: Construction techniques of spanning structure without formwork; (a) Seven Arches made of stone, Gujarat, India; (b) Adobe dome by Hassan Fathy; (c) Nubian Vault Project, Sahel, Africa.

To balance the compression forces within the structure, different types of bricklaying patterns have been developed over time. For example, solid radial brick ribbing, ladder ribbing, lattice ribbing, pitched mud edge-to-edge brick vault, vaulting with edge-to-edge bricks at crown and so on (Figure 5). Overall, the use of different bricklaying patterns in self-standing spanning structures is a testament to the ingenuity and skill of ancient architects and builders, who were able to create structures that are still standing and inspiring designers today.

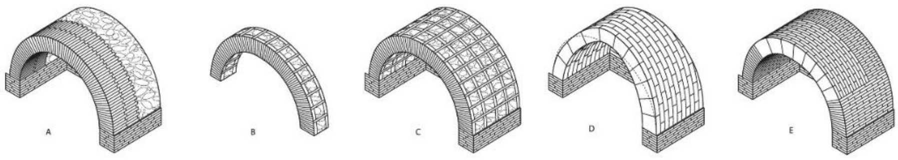


Figure 5: Different types of bricklaying patterns; A. solid radial brick ribbing, B. ladder ribbing, C. lattice ribbing, D. pitched mud edge-to-edge brick vault, E. vaulting with edge-to-edge bricks at crown (Favro & Yegül, 2019).

These structures provide valuable information to take into consideration for 3DCP. In each of the examples, a distinctive bricklaying technique can be observed. Different types of bricklaying techniques from these historic constructions can inspire AM technology to develop new slicing techniques as shown in Figure 6, such as horizontal or corbelling, radial, and inclined, and print them in multi-directions to reduce the overhang angle without needing formwork. Slicing is the method of intersecting a 3D digital model with horizontal planes and dividing it into segments, preparing it for the planning of the toolpath (Ashrafi et al., 2022).

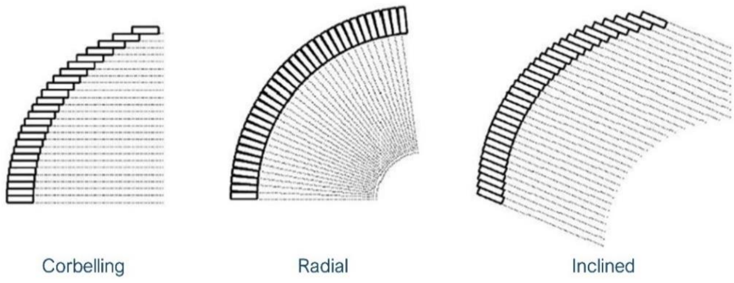


Figure 6: Different types of slicing techniques: horizontal or corbelling, radial, and inclined.

2.3. TOOLPATH DESIGN FOR AM

Additive manufacturing is an innovation that forms 3D objects by adding material layer by layer, which needs a toolpath to follow for printing purposes. One of the most critical challenges of 3D printing on a large scale is toolpath design, which requires designers to parametrize the process. It allows designers to use rules for different shapes and customize them in less time. Toolpath is the computer-controlled movement of a tool in a manufacturing process. In AM, it is the path of the extruder head of the printing machine. Therefore, the process of toolpath design is a critical step in the 3D printing workflow.

The process of 3D printing includes the key steps shown in Figure 7. First, to develop a 3D model, then the model needs to be sliced into horizontal (or corbelling) or inclined layers. Subsequently, a toolpath is generated for material extrusion, and the design is converted into a G-Code file, which is readable by the 3D printer. The 3D printer processes the material by layering it according to the design, following the specified toolpath (The Free Beginner's Guide, 2016). Finally, depending on all printing parameters, it produces the final object at a specific printing time.

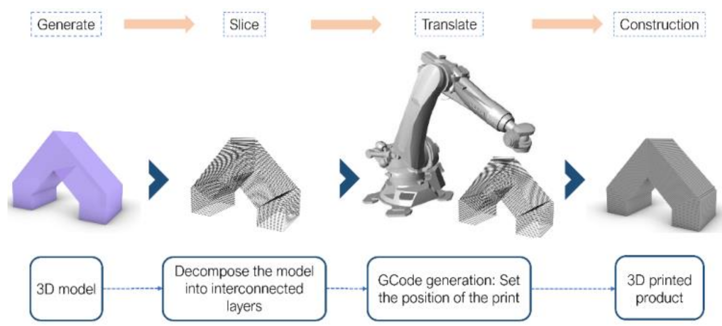


Figure 7: 3D printing process.

2.4. SHAPE GRAMMARS

2.4.1. Shape Grammar for Shape Generation

Shape grammar is a set of rules and principles that can generate a range of designs, serving as a generative system for design exploration and creativity (Stiny, 1980). The generation of new designs is accomplished by using shape transformations like "move", "rotate", "reflection" to match the left-hand side of rules with a part of the current design and then using Boolean operations like "union", "difference", and "intersection" to apply the rules. Initially, the shape grammar concept was used to create grammars for building design by utilizing rules from an existing corpus, which has then advanced to explorations for the generation of new designs, as depicted in Figure 8.

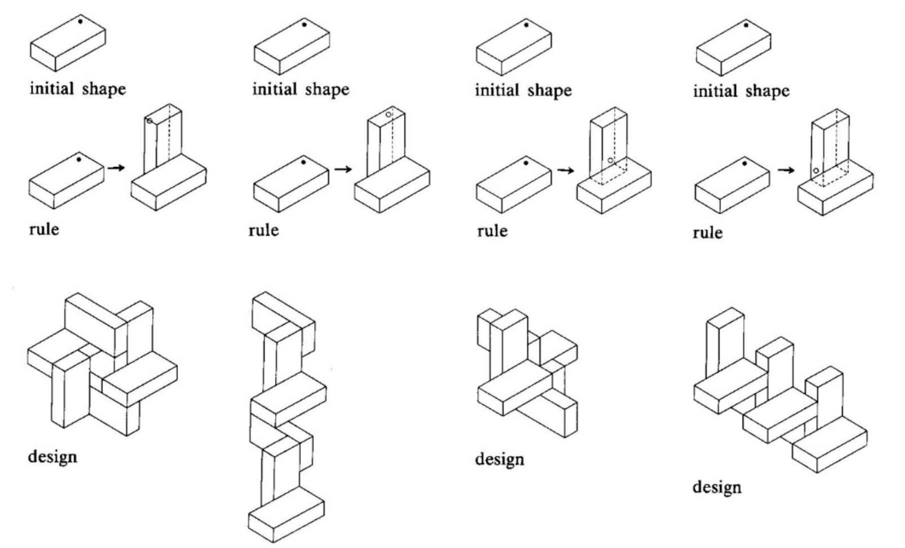


Figure 8: An illustration displays four basic additive rules in shape grammar. By altering the label position on the second added oblong, significant variations in spatial relations and final designs can be achieved (Knight, 1994).

2.4.2. Shape Grammar for Geometric Decomposition

Shape grammar can also be used for geometric decomposition, which involves breaking down complex shapes into simpler parts. This can facilitate the design process by allowing designers to focus on smaller, more manageable components following pre-defined rules. Such an example exists in 3DCP that applies the shape grammar rules on geometry to slice and resize it into layers as shown in Figure 9 (Ashrafi et al., 2022).

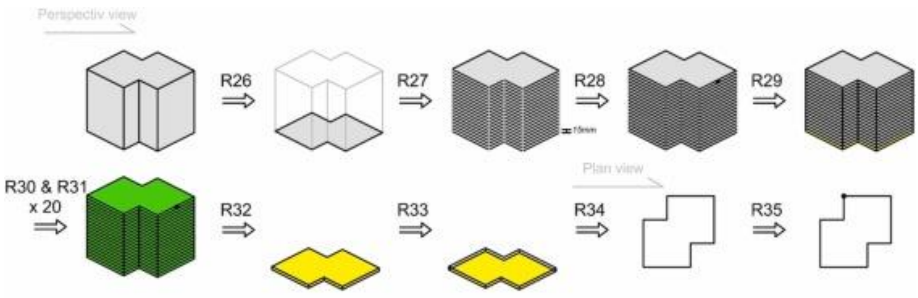


Figure 9: Derivation of a compensated toolpath: implementing the rules of the decomposition grammar and the compensation algorithm to slice and resize the geometry (indicated by the green step) (Ashrafi et al., 2022).

2.4.3. Shape Grammar for Toolpath Generation

In 3DCP, shape grammar can be utilized for toolpath design to generate printable infill patterns and textures. In this context, the shape grammar rules can be utilized to specify the printing path of the robotic arm. Shape grammar can also be used to optimize the toolpath for 3DCP by minimizing the number of tool movements and reducing the printing time. Shape grammar rules have been developed for toolpath design to decompose each layer, trim, and cut the toolpath lines into different infill patterns as shown in Figure 10 (Ashrafi et al., 2022). This is particularly important for large-scale printing projects, where printing time and cost are critical factors.

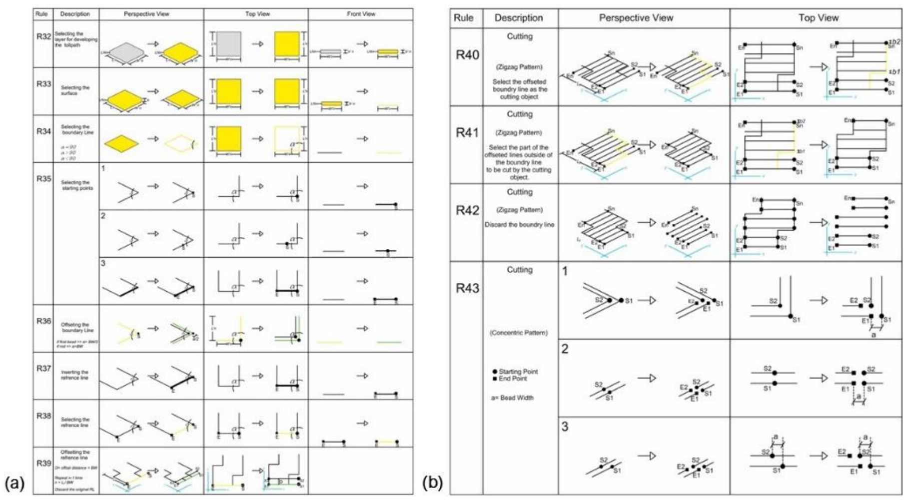


Figure 10: (a) Shape grammar rules for creating the draft of the toolpath on each layer, (b) Shape grammar rules for trimming and cutting the toolpath lines into different infill patterns (Ashrafi et al., 2022).

Shape grammar can be divided into two main types: analytical and original. Analytical grammar is employed to describe and analyze existing designs, while original grammar is used to create new and unique designs from scratch (Ashrafi et al., 2022). This study primarily concentrates on developing original grammars. The proposed grammar is specifically tailored to produce 3D printable shapes and intricately design 3D printing toolpaths, considering specific parameters relevant to concrete printing.

3. Methodology

The broader research methodology aims to develop an algorithm-based design system that generates, simulates, and optimizes the shapes and toolpath required for successful 3DCP. This paper includes only the generation of the shape and toolpath. Simulations have been used only to assess the printability of the designed prototype.

The generator is responsible for producing the overall shape and corresponding toolpath. This generator relies on shape grammar rules and is implemented as a parametric design system, which enables it to generate a wide range of 3D printable shapes. The first shape grammar is designed to generate rules for producing the overall shape of the spanning roof structure, based on historic examples. On the other hand, the second shape grammar generates rules for shape decomposition.

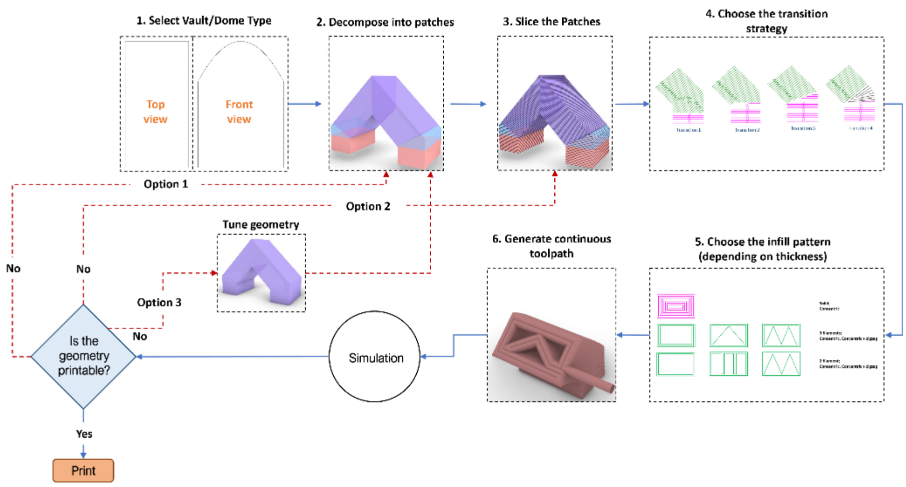


Figure 11: Workflow of the proposed shape and toolpath algorithm.

The workflow (Figure 11) of this system consists of eight sequential steps:

1. Begin by selecting the desired vault or dome type.
2. Decompose the selected geometry into patches.
3. Slice the patches into layers.
4. Decide on the transition strategies between corbelling and inclined slicing techniques.
5. Determine the thickness of the structure, number of filaments, and infill pattern.
6. Generate a continuous toolpath for 3D printing.
7. Conduct a simulation of the designed toolpath.
8. Verify the printability of the structure. If it is printable, proceed to the printing step, and if not, return to the decomposition step or adjust the geometry from the beginning.

4. Developed Rules and Adaptation

4.1. SELECTION OF SPANNING ROOF STRUCTURE TYPE FOR DEVELOPMENT OF SHAPE GRAMMAR RULES

Figure 39 presents various types and boundary conditions of spanning structures identified and listed through literature review. These different types will be used as case studies to develop the algorithm in future work. For preliminary studies, a parametric model will be developed for a barrel vault. In this research, we experimented with combining various slicing techniques to determine the lowest printing angle for a barrel vault. Normally, a barrel vault has a continuous arched shape resembling a semi-cylinder, leading to changing overhang angles on each horizontal layer when sliced. However, for our study, we fixed the arch's angle, resulting in a barrel vault with a rectilinear shape (Figure 12). By adopting this approach, we can investigate the possibility of achieving lower printing angles. Once we determine the feasible printing angles, we can then revert to the semi-cylinder shape if needed.

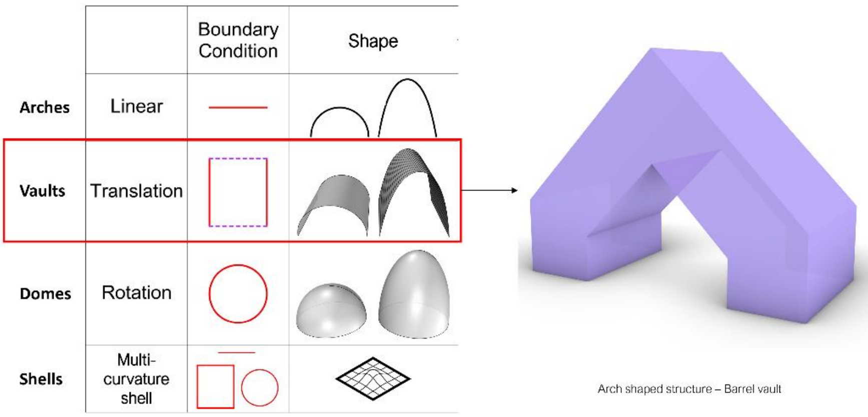


Figure 12: Different types of shapes and the chosen shape for preliminary studies.

4.2. SHAPE GENERATION

Developing a generator algorithm that can decompose complex geometries and create a toolpath with high accuracy and precision is a significant research endeavor. The methodology (Figure 13) of this algorithm involves five key steps. Firstly, an input geometry is given as the starting point. Secondly, the geometry is decomposed into printable patches. Thirdly, different slicing techniques are applied to each of these patches. Fourthly, the toolpath of the transition area is designed. Finally, all the layers are connected to create a single, continuous curve as a toolpath. This approach can be used in a wide range of applications, from manufacturing to architecture and design, making it a valuable tool for future research and innovation.

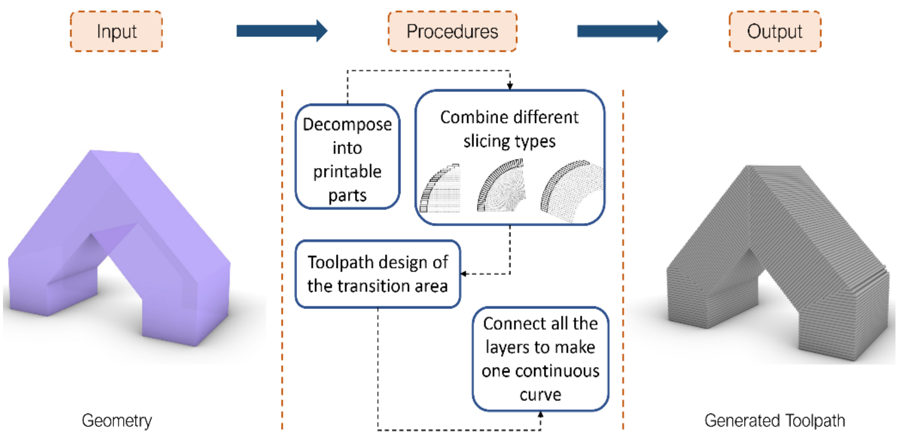


Figure 13: Methodology of the generator.

The shape generation process for a barrel vault follows a step-by-step approach (Figure 14). It begins by selecting a room shape as the initial point. Next, the 2D face of the vault is drawn, and this face is then extruded along the length of the room to form a 3D vault. To add thickness to the vault, an outward offset is applied. These rules outline the barrel vault generation process (Figure 14), making it ready for 3D printing.

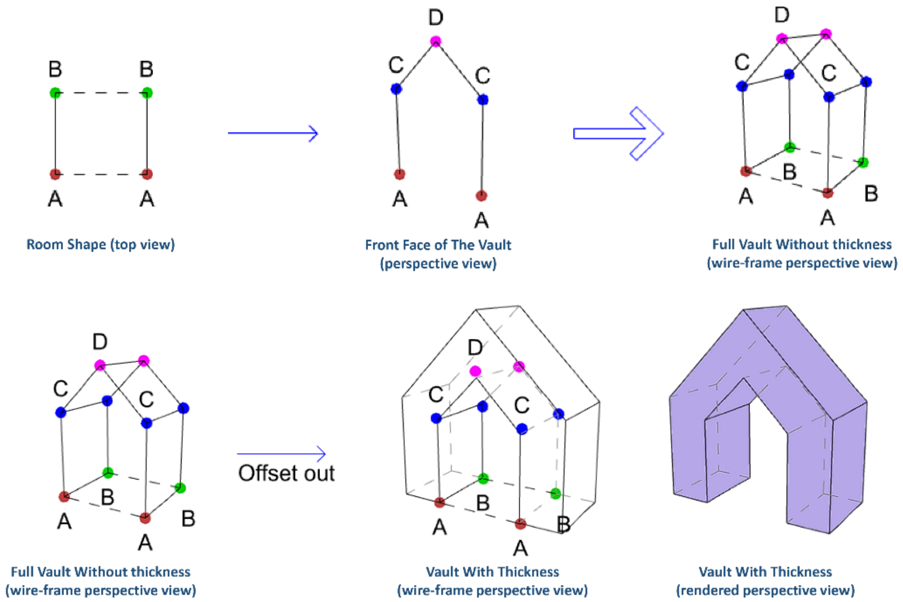


Figure 14: Shape generation rules.

4.3. SHAPE DECOMPOSITION

This section includes the proposed rules to decompose shapes into parts amenable for 3D printing. The decomposition is conducted using parametric modelling. The rules are derived from the printability constraints of the shape and have been translated into parametric rules. An algorithm has been developed consisting of three levels of decomposition, as shown in Figure 15. The three levels of decomposition are as follows:

1. Decompose into printable parts: geometric decomposition.
2. Decompose the parts into layers: slicing the shape.
3. Decompose the layers into filaments: toolpath/infill pattern.

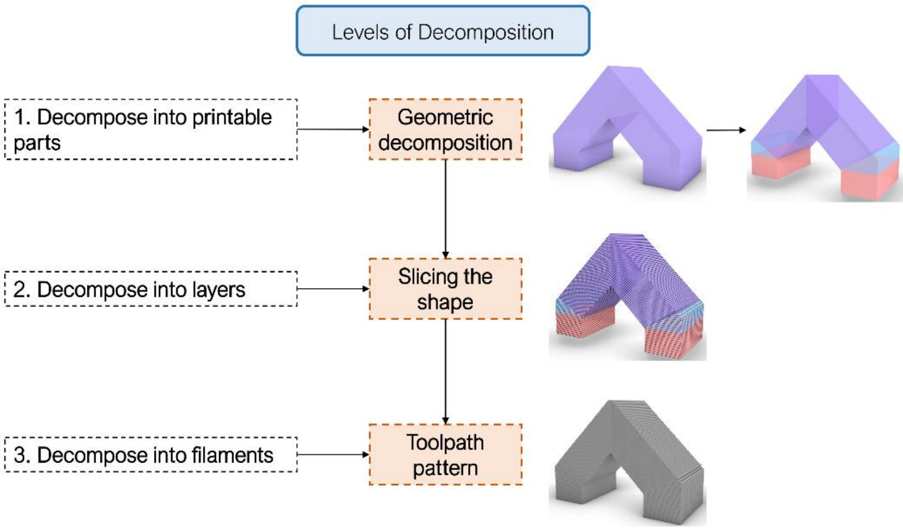


Figure 15: Levels of shape decomposition in 3DCP.

4.3.1. Decomposition of a Building into Printable Parts (Geometric Decomposition)

The shape decomposition rules for a barrel vault encompass a systematic process to facilitate its efficient design and 3D printing as shown in Figure 16. Rule 1 dictates the selection of the front profile. Rule 2 emphasizes working with half of the vault due to its symmetrical nature, reducing redundancy. In Rule 3, the vault is decomposed into horizontal layers. Rule 4 ensures the identification of the non-printable layer, that is at an overhang angle of less than 60°, which requires additional support. Rule 5 involves dividing the shape by a plane originating from that point, aiding in precise segmentation. Rule 6 further divides the shape by a diagonal cutting plane, to make it able to slice it in non-horizontal layers. Rule 7 focuses on decomposing Part B into inclined layers. Finally, Rule 8 designates Part C as the transition section, contributing to the smooth integration of the different types of slicing.

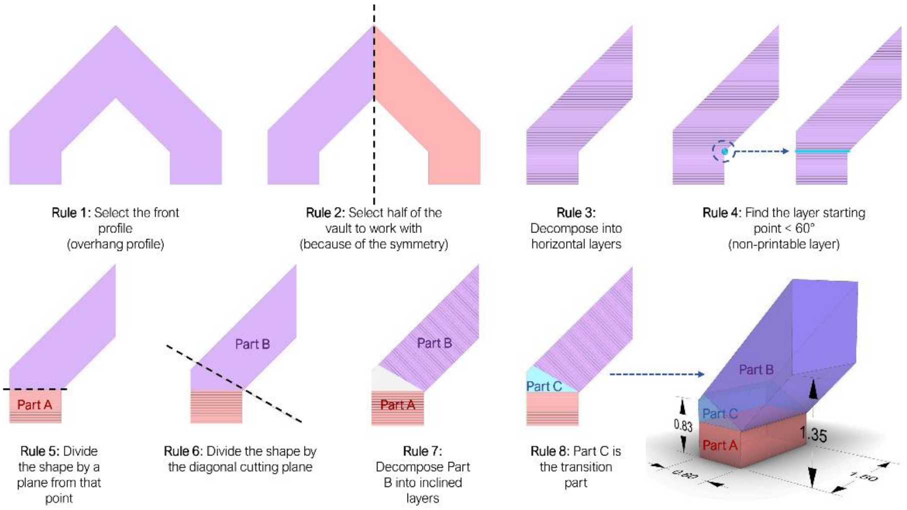


Figure 16: Geometric decomposition rules.

Figure 17 visually illustrates the implementation of the decomposition rules for the barrel vault. The vault has been divided into three distinct parts: Part A utilizes corbelling slicing, Part B employs inclined slicing, and Part C serves as the transition part, accommodating corbelling, inclined, radial, or hybrid slicing methods.

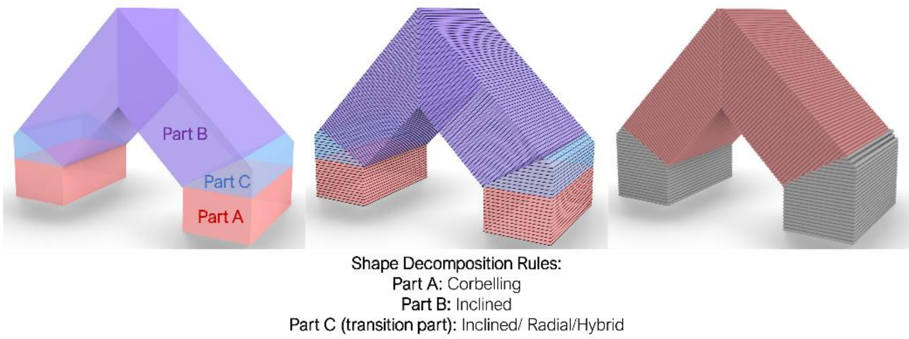


Figure 17: Implementing the decomposition rules on the barrel vault.

4.3.2. Decomposition of Patches into Layers (Slicing the Patches)

The parameters that were considered for the test experiments included the angle of printing, slicing techniques, toolpath design strategies for transition areas from one slicing type to another, infill pattern, and the number of filaments for toolpath design.

The parameters of test experiments are:

1. The angle of printing is 45°.
2. Four different types of slicing strategies have been developed for the transition areas, as shown in Figure 18. Transition 1 starts with inclined layers from a lower layer, while Transition 2 starts with inclined layers at the beginning of an overhang. Transition 3 involves overlapping horizontal and inclined layers, creating a staggered pattern, while Transition 4 combines corbelling, inclined, and radial layers in the transition area.

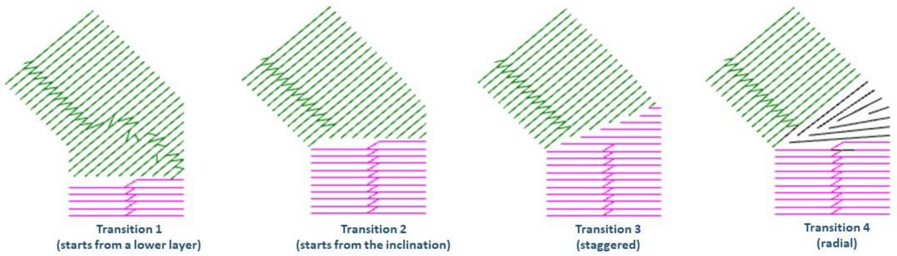


Figure 18: Strategies for transition areas from one slicing type to another.

4.3.3. Decomposition of Layers into Filaments (Toolpath and Infill Pattern)

In terms of toolpath design, there are various types of infill patterns and numbers of filaments that can be explored. Figure 19 shows the different types of infill patterns that have been developed for these experiments, featuring solid concentric patterns and different combinations of concentric and zigzag patterns, depending on the number of filaments involved.

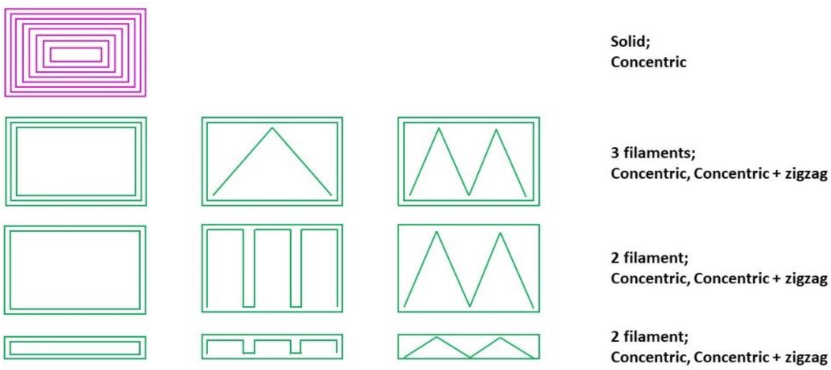


Figure 19: Infill pattern and number of filaments for toolpath design.

5. Validation

To print half of a barrel vault with 45° overhang, Transition 1 was chosen, along with a solid concentric toolpath on the corbelling part and 3 filaments of concentric + zigzag pattern on the inclined part, as shown in Figure 20. The toolpath design for the full barrel vault is shown in Figure 21a, while the sectional perspective shows the infill patterns in Figure 22b.

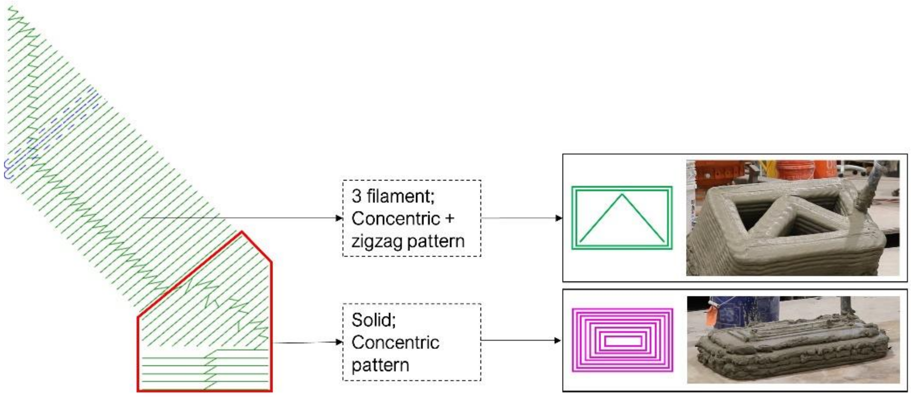


Figure 20: Toolpath design for first test experiments.

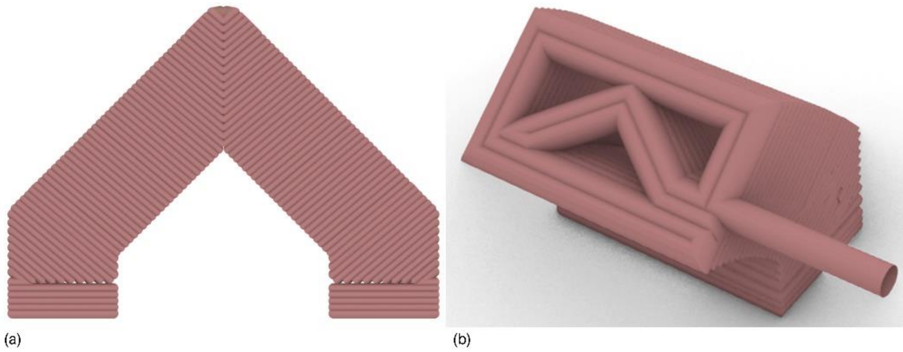
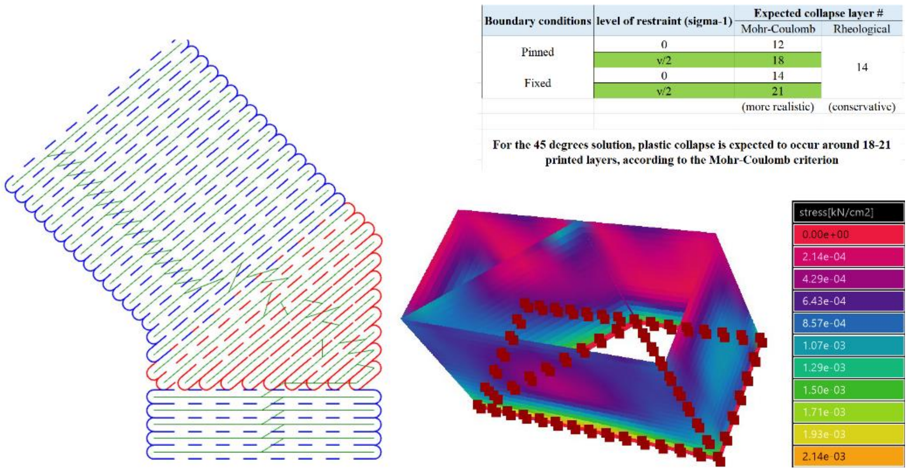


Figure 21: Toolpath design of the model of first test experiments; (a) front view, (b) sectional perspective showing the infill patterns.

For simulating the collapse of the printed models, the algorithm developed by Goncalo Duarte from Penn State was utilized (Duarte et al., 2023). The simulation results indicated that the 45-degree model may collapse between 18-21 inclined layers (Figure 22). Therefore, the toolpath was designed and prepared up to 22 layers for the subsequent test experiments in order to assess the simulation result.



Boundary conditions	level of restraint (sigma-1)	Expected collapse layer #	
		Mohr-Coulomb	Rheological
Pinned	0	12	14
	v/2	18	
Fixed	0	14	
	v/2	21	
		(more realistic)	(conservative)

For the 45 degrees solution, plastic collapse is expected to occur around 18-21 printed layers, according to the Mohr-Coulomb criterion

Figure 22: Numerical simulation results showing the collapse for the test experiments. Credit-Goncalo Duarte.

Figure 23 displays the prototype measuring 0.8 feet in width, 1.5 feet in length, and 1.50 meters in height that has been 3D printed using a combination of corbelling and inclined slicing techniques with a multi-directional strategy in the AddCon Lab. The 45-degree prototype was successfully printed without any collapse, and the overhang angle of printing was successfully reduced to 45 degrees.

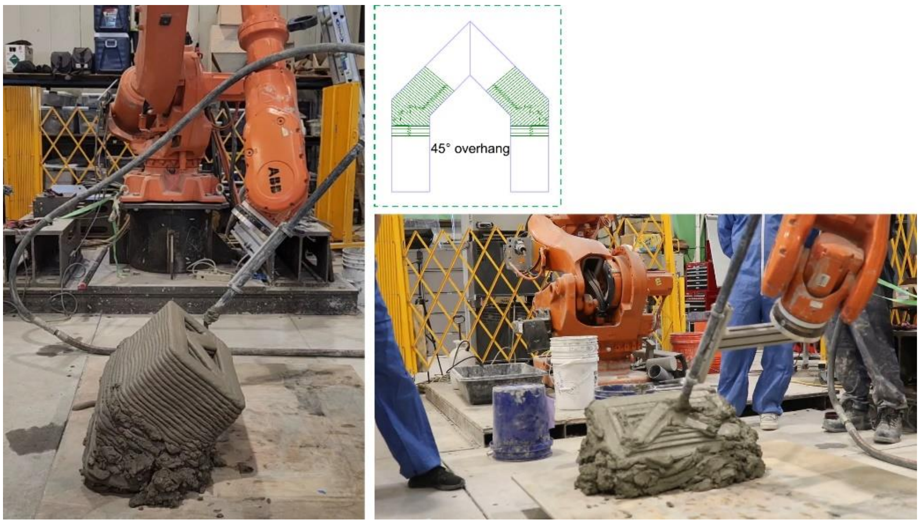


Figure 23: Prototype with 45 degrees overhang angle.

6. Conclusion

The preliminary algorithm that has been developed successfully supports the generation of the overall shape, its decomposition into printable patches, the slicing of the patches into layers with varying angles, and the creation of toolpaths for each layer with varying numbers of filaments and types. By accomplishing these tasks, the algorithm can be used to reduce the pitch height of a barrel vault to a shallower level while still ensuring printability.

The printed prototype serves as a demonstration to evaluate the feasibility of multi-directional printing, assess the simulation tool, and verify its consistency with the experimental results. Future endeavors will encompass complete barrel vault printing as part of ongoing research. Testing all the other techniques for the transition part will be a part of the next experiment as well. The radial printing was not tried in this paper which should be tested in the next step.

It is crucial to emphasize that the proposed algorithm represents an initial stage in a broader research agenda aimed at developing a comprehensive model of the printing process. Future work will tailor the developed algorithms and create an automated prototype software for shape decomposition and toolpath generation. Currently, the focus of this proposed algorithm and shape grammar rules is only on spanning structures. In the future, the scope of work may expand to encompass a broader range of shapes, along with the development of comprehensive shape grammar rules, resulting in a more versatile and generic algorithm. This research introduces a multi-directional printing strategy as an efficient method to achieve overhang angles lower than 60 degrees. Subsequent work will focus on conducting additional experimental studies to explore other printing techniques.

Acknowledgments

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GRAVITY-DRIVEN SAND DYNAMICS

A Technique for Optimizing Self-Organizing Dune Sand Patterns using Pouring, Gravity and Multi-Objective Computation

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Abstract. The paper offers an in-depth review of a digital/analog process for making sand-based patterns that can be computationally optimized as panels. These systems are intended for desert environments featuring dune sand as a primary material context. The paper discusses how the self-organization of dune sand can create patterns for shading and become computationally optimized for potential architectural outcomes in the form of a weather-responsive panel. Evolutionary computation assists in the methodology for performative design by incorporating weather-based analytics for sun, UV, heat, and wind. The methodology allows for material optimization that results in a series of design options that are highly responsive to local desert conditions using dune sand as the primary material. It begins with experiments in self-organizing sand sequences based on naturally occurring dune sand configurations. It then isolates the self-organizing characteristics atop localized laser-cut planes that allow the sand to pour and pile into specific configurations. The opening size and the number of openings were then studied, and configurations were frozen with a binder and used in a manifold of physical surface sequences. The project employs an optimization of these sand configurations based on the best possible arrangements for the size and number of openings that generate self-organized piles in a demonstrated desert location. The role of this computational and material process adds to the current dialogue of designing in extreme arid environments and aligns with the UN sustainability goals for sustainable communities, climate action, responsible consumption and production.

Keywords: *dune sand, computation, self-organization, technology, regional material*

ملخص. تقدم الورقة مراجعة متعمقة للعملية الرقمية/التناظرية لصنع أنماط قائمة على الرمال يمكن تحسينها حسابيًا على شكل لوحات. هذه الأنظمة مخصصة للبيئات الصحراوية التي تتميز بالرمال الرملية كسياق مادي أساسي. تناقش الورقة كيف يمكن للتنظيم الذاتي لرمال الكثبان الرملية أن يخلق أنماطًا للتظليل ويصبح مُحسّنًا حسابيًا للنتائج المعمارية المحتملة في شكل لوحة تستجيب للطقس. يساعد الحساب التطوري في منهجية التصميم الأدائي من خلال دمج التحليلات المستندة إلى الطقس للشمس والأشعة فوق البنفسجية والحرارة والرياح. تسمح المنهجية بتحسين المواد مما يؤدي إلى سلسلة من خيارات التصميم التي تستجيب بشكل كبير لظروف الصحراء المحلية باستخدام الكثبان الرملية كمادة أساسية. يبدأ الأمر بتجارب في تسلسلات رملية ذاتية التنظيم تعتمد على تكوينات رمل الكثبان الرملية التي تحدث بشكل طبيعي. ثم يقوم بعد ذلك بعزل خصائص التنظيم الذاتي فوق الطائرات الموضعية المقطوعة بالليزر والتي تسمح للرمل بالصب والتكديس في تكوينات محددة. تمت بعد ذلك دراسة حجم الفتحة وعدد الفتحات، وتم تجميد التكوينات باستخدام مادة رابطة واستخدامها في مجموعة متنوعة من تسلسلات السطح المادي. يستخدم المشروع تحسين هذه التكوينات الرملية بناءً على أفضل الترتيبات الممكنة لحجم وعدد الفتحات التي تولد أكوامًا ذاتية التنظيم في موقع صحراوي مثبت. ويضيف دور هذه العملية الحسابية والمادية إلى الحوار الحالي حول التصميم في البيئات القاحلة للغاية ويتوافق مع أهداف الأمم المتحدة للاستدامة للمجتمعات المستدامة والعمل المناخي والاستهلاك والإنتاج المسؤولين.

الكلمات المفتاحية: *الكثبان الرملية، الحوسبة، التنظيم الذاتي، التكنولوجيا، المواد الإقليمية.*

1. Introduction and Contextualization of Endeavor

This research explores the potential integration of a regionally suitable architectural system using dune sand as a material and computational processes for optimization. The aim is to facilitate the utilization of an innovative material agenda centered around local desert dune sand, to describe an optimization method for unique panels that can adapt to different locations and environmental needs, and to illuminate options for sustainability in the global south. Sand is a critical global resource; projections from the UN for 2060 highlight sand as the foremost consumed construction material (Fagan, 2020). Previous UN studies in 2011 and 2017 accurately predicted the escalating demand for sand and small aggregates, surpassing other construction materials, and forecasted the extensive extraction and utilization of sand well into the future. This information sheds light on a multitude of environmental challenges due to mining, habitat degradation, and worldwide importation.

In the Middle East and North Africa (MENA) region, cities import substantial quantities of river sand from Southeast Asia and Australia to meet concrete and masonry needs (Rayasam, 2016). This thesis examined the self-organization and amalgamation of sand with a specific water-based binder under laboratory conditions, concluding that, under specific circumstances, this behavior can be manipulated to create a series of thin panels and tiles with distinct geometries and openings, while speculative in nature, brings about a robust dialogue for the future of architectural materiality and computation in the desert.

The investigation underscores the feasibility of leveraging local dune sand resources to create prototypical elements, such as mashrabiyas and jalis, that can cater to spaces necessitating ventilation, enhancing human comfort in arid desert environments. It utilizes these typological elements to remain consistent and in context with architectural traditions that have existed for hundreds of years. With these concepts in mind, a design workflow has been devised, utilizing both analog and computational tools to articulate contextually relevant architectural outcomes using dune sand and predictive self-organization. The methodology ultimately revealed the creation of planar systems and discrete units that simulated breeze walls. These were studied to generate a range of performance-based compositions amenable to precise programming and site-specific conditions. Employing Grasshopper, Wallacei, and Ladybug, the performance-driven logic for these compositions can be calibrated based on solar and wind data.

Given the instability of dune sand, desert regions have become dependent on imported materials from outside the region. This research highlights the potential of dune sand as an ongoing line of inquiry for material exploration, underscoring the limited architectural research being done with this particular material. This research trajectory aligns with populations residing in harsh desert environments, synergizing this culture with bio-sand material and computational design. The project responds to urgent global concerns outlined in UN Sustainable Development Goal SDG11, "Sustainable Cities and Communities." By contributing to the design of resilient and sustainable urban settlements and formulating materials that mitigate the environmental impacts of urbanization, it fosters resource efficiency within sustainable and robust construction practices. Additionally, it aligns with UN Sustainable Development SDG13, "Climate Action," by reducing greenhouse gas emissions tied to global transportation and importation. (U.N., 2020)

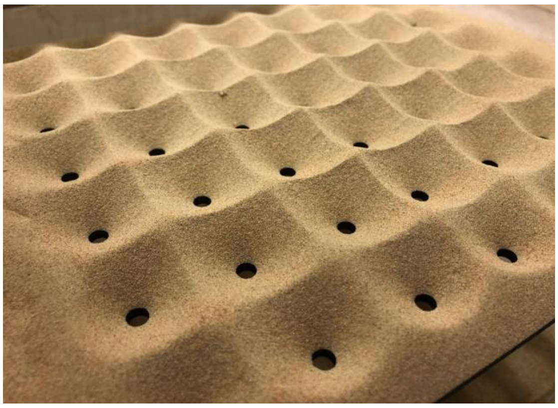

Figure 1. Dune Sand Material Experiment, M. Farr

The methodology commences with self-organizing material experiments involving sand as a constituent component and progresses through a range of physical sand pouring to establish an optimization sequence gleaned from a manifold of computational tests (Figure 1). The computational parameters delineate a series of performative outcomes tailored to sand panel design, leveraging the thickness of poured sand, material density, and the opening dimension on a given panel. Close attention is given to the use of opening, the size of the opening, and the number of openings on any given sand pour. The outcomes present an ongoing adaptability in forming various configurations suitable for potential planar systems with permeable qualities akin to ventilated mashrabiyas and jalis.

1.1. TECTONIC CONTEXT

This research sheds light on potential local opportunities to design and develop thin, sand-based panels in the Sahara and Arabian deserts. Utilizing dune sand resources abundant in the region, the work demonstrates a new craft that is contextually appropriate, building upon indigenous traditions while demonstrating a technique for optimization. In contrast to options such as concrete or masonry, which heavily rely on a significant amount of imported resources, this solution offers a heightened level of sustainability for local projects by using dune sand as the material. To achieve UN sustainability targets, a diligent exploration of applications for local, available resources within extreme environments is essential. The Arabian desert was selected as a particularly pertinent backdrop to contextualize this endeavor due to the presence of dune sand and the prevalent use of mashrabiyas.

The availability of specific building materials has historically shaped Indigenous architectural practices in this locale. Traditional modalities used materials such as sandstone, mud, arish, coral stone, and rock, especially along coastal regions (Hattstein, Delius, 2013). Moreover, nomadic tribes navigating the desert terrain ingeniously incorporated fabric into their architecture. This lightweight material offered inherent flexibility, enabling facile adaptation to varying climatic conditions and portability via camelback. Many mud and earth structures remain, yet stand-alone structures made exclusively of desert dune sand are much harder to find.

There is a substantial surplus of dune sand, a resource paradoxically underutilized in construction endeavors in the Middle East. For example, concrete and asphalt utilize marine sand, not dune sand. Interestingly, modern metropolises such as Dubai, Sharjah, Abu Dhabi, and Jeddah are surrounded by vast regions of dune sand. However, this resource remains largely unused, and desert construction projects specify imported sand from Australia and South Asia. (Beiser, 2016) From a design perspective, it is counterintuitive that these regions resort to alternative sand variants from foreign locales to fulfill all construction needs. River sand is favored due to its perceived superiority in quality for architectural and manufacturing purposes; it is triangular in shape rather than round like dune sand (Al-Ghandour, 2004). River sand is transported via maritime routes from Southeast Asian and Australian origins to facilitate the production of concrete, glass, mortar, and blocks, thereby amplifying the carbon footprint and compromising the overall sustainability of architecture within the vicinity. Consequently, the role of the desert in modern construction emerges as a pivotal question, coupled with the opportunities afforded by this distinct scenario.

1.2. FUNCTIONAL ISLAMIC REFERENCES FROM THE REGION

A *mashrabiya* is a distinctive architectural element found in traditional Islamic architecture, primarily in the Middle East and North Africa (Archnet, 2023). Its significance lies in its multifaceted role as a functional and cultural component. This intricate lattice-like screen serves as a climatic mediator, filtering harsh sunlight, allowing ventilation, and maintaining privacy within interior spaces (Serageldin, 1980). Its geometric patterns create combinations of light and shadow, transforming ordinary environments into more comfortable spaces (Bierman, 1983). Beyond its practical attributes, the mashrabiya carries cultural and social importance, reflecting the values of modesty, privacy, community, and the seamless integration of these with architecture (Petruccioli, 2000). It symbolizes the connection between indoor and outdoor realms, allowing occupants to engage with their surroundings while maintaining a sense of sanctuary (Kuban, 1985). The mashrabiya thus exemplifies how architectural elements can harmoniously merge functionality, aesthetics, and cultural identity, all of which can enrich the built environment. (Elhassan, 2010).

The term *jali* signifying "net," refers to a perforated lattice screen, also found in Islamic architecture and blends function and local craft by filtering sunlight and moderating climate, (Met, 2020). In this research, both of these typologies are used as references which are then algorithmically crafted to resonate with the context. Computation aids in arranging and calibrating the openings in planes and optimizing the resultant sand piles that form on top of the planes.

2. Material Attributes and Behaviour of Dune Sand

Desert dune sand and river sand are similar natural aggregates, but they possess distinct physical material properties that influence their suitability for construction. Desert dune sand, typically derived from arid regions such as the Arabian Desert, exhibits unique wind-blown characteristics compared to river sand, which originates from water bodies. Regarding grain size and distribution, desert dune sand tends to have a well-sorted and finer grain size compared to river sand (Al-Ghandour, 2004). River sand, influenced by water currents, can have a broader range of particle sizes and is often coarser in nature (Sadek, 2012). This difference impacts the packing density and stability of the sands. Dune sand's fine grains contribute to a denser, more compact arrangement, while river sand offers better material interlock due to its mix of coarse and fine triangular particles. Porosity is another distinguishing factor. Desert dune sand typically has lower porosity due to its dense, closely packed grains, making it less permeable to water than river sand (Al-Rawas, 2012).

However, despite its unique properties, desert dune sand is generally not favored for construction due to several limitations. One crucial factor is its lack of adequate cohesion and particle angularity (Fawcett, 1972). Desert dune sand's rounded grains result from aeolian processes, reducing interlocking binding capability and overall strength. River sand, with its more angular particles, provides better stability and load-bearing capacity. Moreover, desert dune sand often contains a higher salt content due to its arid origin (Al-Abdul, 2012). This salinity can pose significant durability challenges in construction, promoting corrosion in steel reinforcements and causing long-term structural issues.

River sand is preferred in construction due to its better mechanical properties, including cohesion, angularity, and compactness (Ahmad, 2017). Its diverse grain sizes and particle shapes enhance interlocking, making it suitable for creating stable aggregates in concrete and mortar. River sand's proven use in construction applications, alongside its availability and relatively consistent quality, further contribute to its preference over desert dune sand.

In summary, desert sand is characterized by distinct attributes compared to its marine counterpart. River sand exhibits sharp angularity due to water-borne conditioning rather than aerial dynamics. Its elevated quartz content and compaction compatibility render it an efficacious constituent within concrete admixtures. Conversely, desert dune sand assumes a rounded morphology, an effect of aerial abrasion, thus resembling a collection of marbles in their configuration. The particles manifest smooth surface textures, presenting an exceedingly fine particle size. It is slightly alkaline and attains a density akin to soil, collectively rendering it less amenable to contemporary construction methodologies.

3. Self-Organization and Predictive Material Behaviour

The self-organizing nature intrinsic to sand is exhibited during pouring, leading to the formation of a characteristic funnel with a natural angle of repose, as illuminated by the architectural investigations of Frei Otto. The 34-degree angle of repose for sand, a critical aspect of granular material behavior, is an important factor to understand regarding the self-organization phenomena. It represents the maximum slope at which a pile of dry sand maintains stability before collapsing. As a self-organizing system, sand particles interact based on local rules, leading to emergent patterns and structures. In this research, that moment becomes the starting point for predictive computational behavior. As sand grains accumulate, their natural tendency to settle at the angle of repose contributes to the formation of piles and patterns. These piles reflect a balance between gravitational forces and friction, embodying the principles of self-organization, where simple interactions give rise to complex forms. Frei Otto's sand experiments, for instance, explored self-organization through sand's inherent ability to find equilibrium shapes. The angle of repose serves as a tangible link between granular physics and the broader concept of self-organization in diverse natural and engineered systems (Hunt 1963, Llorens, 2009).

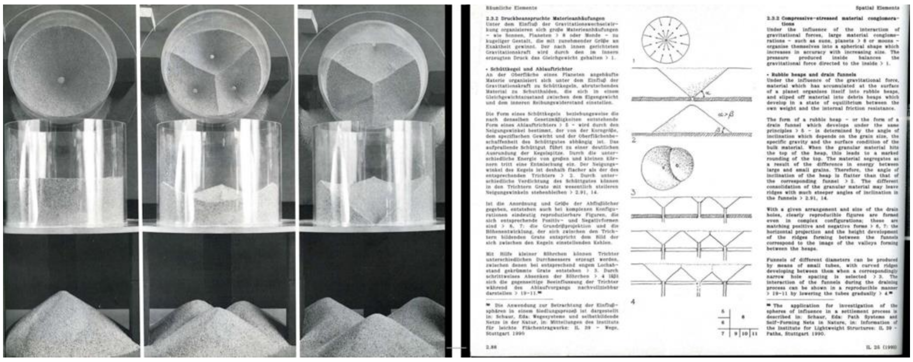

Figure 2. Finding Form, Spatial Elements, p. 288, IL 25, 1990, Otto

Otto conducted his experiments involving sand to explore the principles of self-organization in architectural structures (Figure 2.). He used sand to simulate natural processes, allowing grains to settle into equilibrium shapes (Otto, Rasch, 1995). By pouring sand onto various surfaces and observing how it spontaneously formed intricate patterns, Otto sought to understand how structures could emerge. His experiments revealed the inherent capacity of materials to organize themselves under specific conditions. (Llorens, 2009) Otto's sand experiments exemplified his belief in harnessing nature's efficiency and adaptability to create efficient and sustainable architectural solutions, paving the way for integrating self-organizing principles in modern architectural practices. This project builds upon that research by utilizing desert dune sand to respond to specific openings on planes.

4. Methodologies

When sand is piled on an articulated plane or “limited plane," the shape of the plane can begin to affect the shape of the pile. This can be seen in the image (Figure 3) by Matematica (Matematica, 2023). This is much different than making sand piles on an infinite plane, ground plane, or digitally in a computer. For example, in the physical world, a round, lifted plane creates a different pile than a rectangular lifted plane, and so on. When sand is poured onto a lifted plane and accompanied by openings, the sand pile's organization is affected even greater based upon the opening and proximity to an edge. The organizational behavior of sand allows it to be aggregated naturally based upon a specific set of criteria, mainly: resting plane, angle of repose, gravity. This is a critical point in the project because it makes a controlled sand pile with specific depth and geometry, which is potentially a controllable architectural surface condition.

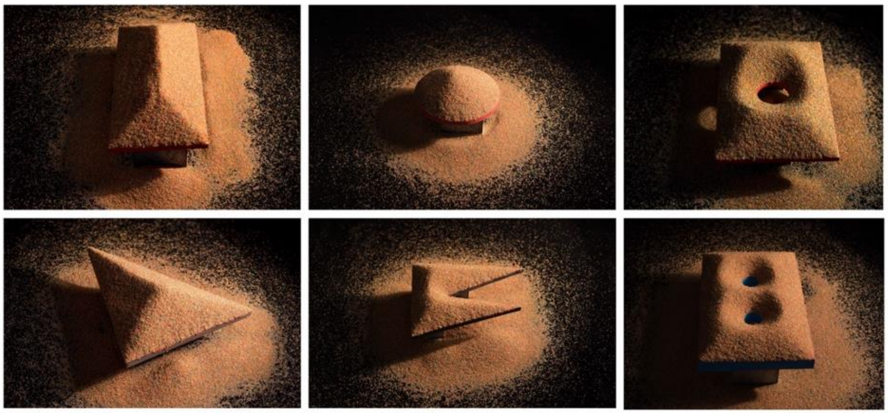

Figure 3. Poured sand on raised planes, Matematica, Argenton

In summary, when sand is poured onto an articulated surface, it forms distinctive patterns driven by the balance between gravity, friction, and particle interactions. As the plane's shape and opening change, the sand grains accumulate to create different geometrical configurations. These patterns emerge due to the dynamic interplay between the sand particles' accumulation and the plane's changing orientation. Through experimentation, this process reveals that the plane's geometry greatly influences the sand's behavior. The sand forms narrow ridge patterns on longer planes. Conversely, broader planes result in more dispersed patterns. The sand's resultant pile changes in response to the plane's angle in plan; this highlights the intricate nature of granular material dynamics and showcases the rich complexity that emerges from seemingly simple interactions.

4.1. SAND PILE SIMULATION COMPUTATION

In the process of constructing a digital model to depict the physical dynamics of sandpiles and the angle of repose, employing 25 distinct sand piles, it becomes evident that any adjustment made to one pile results in a consequential impact on the neighboring piles due to the altered sand distribution. To explore this phenomenon, a series of digital simulations were conducted, initially shifting the positions of the first two sand piles and subsequently progressing through a spectrum of pile movements until all 25 piles underwent modification (Figure 4). These simulations effectively captured the sandpile's behavior of the top of the pile as a pattern density and the bottom of the pile as a shape, offering insights into the pile behavior and interactions.

This digital model was then aided by a Grasshopper definition, whereby the placement of points on a plane also corresponded with an angle of repose and a resultant cone replicating the material behavior of sand. This creates a generative condition for the sand based on the point grid and the behavior of piling conditions along with the 34-degree angle of repose. When placed together on a planar surface, the sand piles create a series of Thiessen Polygons, also described as a Voronoi grid. This occurs naturally on an infinite plane. Different simulations were run based upon different numbers, and the same behavior can be seen from planar compositions of 10 points, up to 1000 points, and beyond, each time with the same predictive outcome whereby the Voronoi pattern became more or less complex depending on the number of points, distance between, and the number of resultant sandpiles.

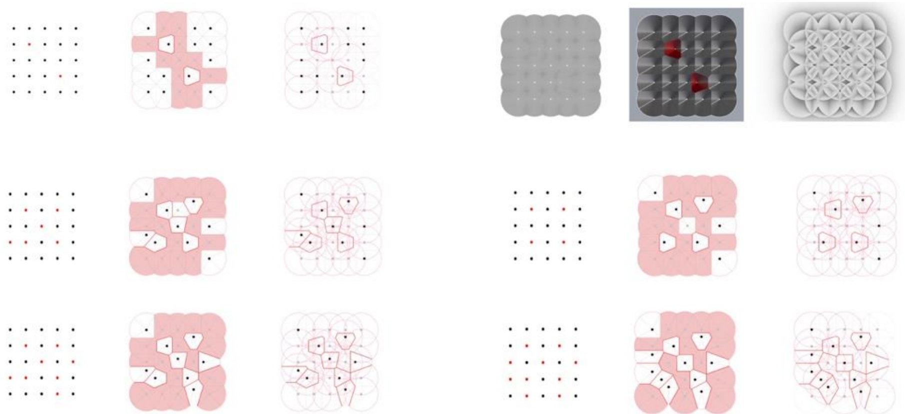

Figure 4. Sand-pile computation model, Farr

The Voronoi grid's computational logic involves partitioning an area into regions around a set of seed points. Each point in the space belongs to the region of the nearest seed point. This process entails calculating distances between each point and the halfway point between the seeds. The resulting grid consists of polygonal cells, with each cell encompassing the area closer to its corresponding seed point than any other. These grids efficiently allocate an amount of dune sand based on proximity relationships and the angle of repose. The angle of repose is the factor that contributes to height and three-dimensional form and the resultant shadow pattern.

4.2. COMPUTATION WITH ANALOG MACHINE

Following the computational mockup of the sandpile behavior, a testing machine was built as a pouring mechanism to respond to the ongoing series of planes and points generated using the computational algorithm (Figure 5).

This was done to compare physical piles with digital piles and to attempt to control sand piles as three-dimensional surfaces with predictive intelligence. The apparatus comprised a sliding tray and box auger system capable of accommodating laser cut acrylic sheets with varying point grids. The process continued with acrylic sheets subjected to laser cutting, guided by specific points derived from a series of tests generated through computational modeling. Positioned beneath each tray was a reservoir for holding sand, complemented by an auger dumping mechanism to regulate the sand's flow directly onto the acrylic sheet. The machine accommodates the use of multiple sheets concurrently to make larger studies or can be configured for single-sheet operation. Notably, this apparatus ensures the recycling and reutilization of all sand. Additionally, it incorporates a recording station and a lighting station to systematically document the sand flow patterns and their resulting manifestations. This machine offers a comprehensive physical platform for investigating various aspects of sand piles, including topography, weight distribution, and sidewall characteristics. Moreover, it facilitates the manipulation of opening sizes on the plane, thereby offering different levels of performance and adaptability.

In this context, digital fabrication transcends the conventional notion as a detached procedure and takes on the role of a collaborative analog/digital endeavor with an ongoing series of one-to-one outcomes. The dynamic interaction between digital computation of points and the tangible characteristics of the material becomes apparent as the panels take form, arising from a mutually beneficial synergy of material responsiveness and computational rationale.

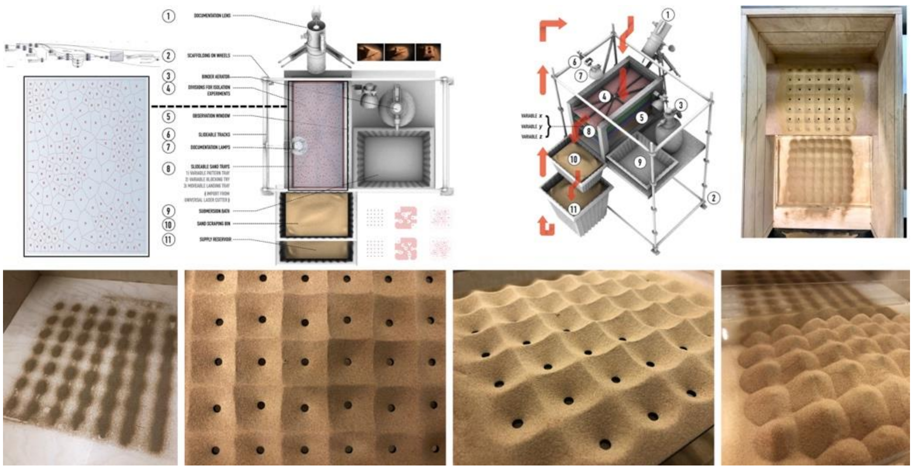

Figure 5. Sand-pile generation, digital to analog machine, Copyright, Marcus Farr 2023

4.3. OPTIMIZATION OF OPENINGS, EVALUATION, AND WEATHER DATA

The examination of the different size apertures within the planes was extended to include their role as a contributing form-finding factor alongside the organizational characteristics of the sand (Figure 6). From a design perspective, the placement of points, the introduction of apertures as potential ventilation areas, and variations in shadow densities are intrinsically interconnected. Additionally, they correlate with the depth and overall weight of the sand pile. Notably, a higher number of apertures corresponds to a reduction in weight, a critical consideration given the substantial density of sand. Furthermore, an increased quantity of apertures results in more pronounced shadow patterns, which could hold particular significance in desert architecture. This is because the primary objectives for a surface are to safeguard the building's facade while simultaneously providing avenues for effective ventilation and heat dissipation.

Using the openings and placement of points for the different sandpiles, an optimization strategy using Wallacei was introduced to enable the project to be studied more thoroughly using computation and simulation (figure 7). Wallacei is a multi-objective optimization engine that creates and runs evolutionary simulations utilizing useful information from the point placement that makes up the Voronoi grids, the resultant sand piles, and the tile sequences generated in Parakeet. This can help make more informed decisions at all stages of the sand pile system as a predictive simulation. The optimization method can be utilized to achieve material efficiency, and to understand how sand pile panels can be more useful in potential architectural projects.

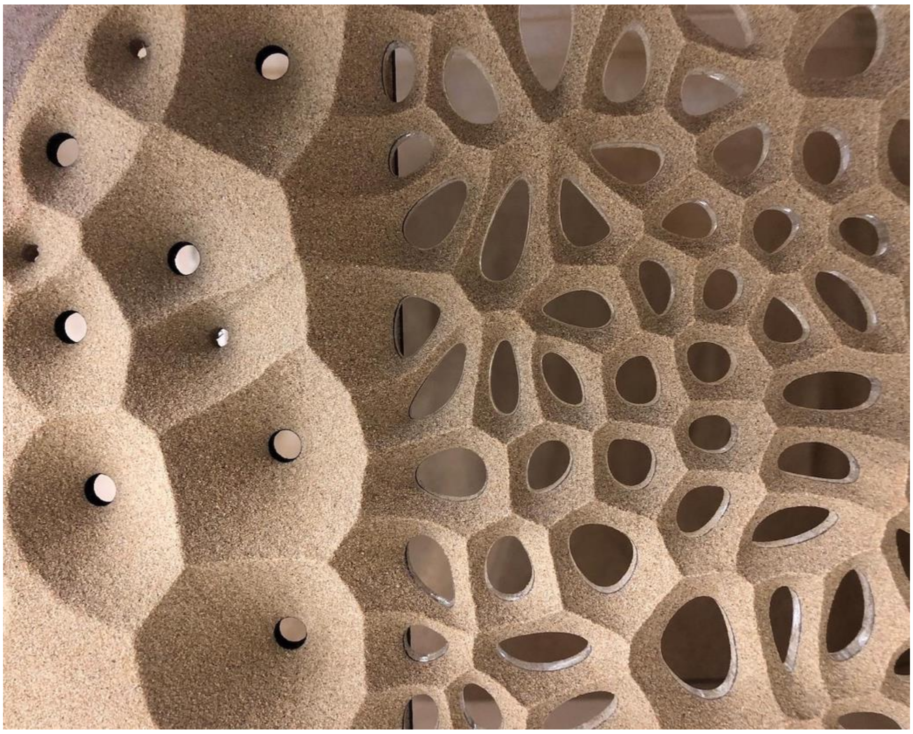

Figure 6. Sand-pile panel with optimized openings, Farr

To understand the digital logic further, in science, a genotype represents a collection of guidelines that serve as a basis for shaping a phenotype. Essentially, the phenotype is the basic physical manifestation of the genotype. For example, an individual's genotype represents their distinctive DNA sequence. This concept pertains to the two DNA forms that a person has inherited from both their mother and father for a specific gene. In contrast, the phenotype relates to the observable expression of this genotype, essentially encapsulating an individual's external appearance. Within this project, the genotype serves as a set of principles for geometry and aesthetics, ultimately giving rise to a phenotype that can be suitable for a specific desert context. The variations of these can be used to study different presentations of sandpile sequences that become panels or tiles. Fitness objectives work to define the specific objectives or constraints in order to make them meaningful for specific criteria.

A fitness value, a genotype, and a phenotype are three distinct concepts, often used in the context of genetic algorithms and evolutionary biology. They differ in that a genotype refers to the genetic information or genetic code of an organism or individual, or geometry.

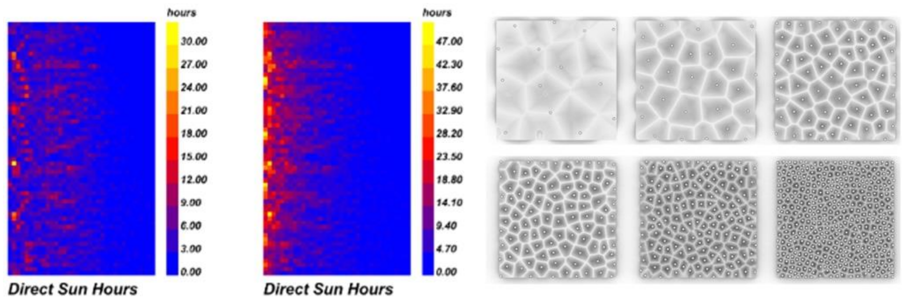

Figure 7. Optimized opening simulations, Farr

Genotype represents the specific genetic instructions that an individual carries, which are often encoded in DNA or other genetic material. Comparatively, Phenotype refers to the observable physical and functional traits. It is the result of the interaction between an organism's genotype and its environment. Phenotypes can change in response to environmental factors. The fitness value is a measure of how well an individual's genotype performs in a specific context, often in the context of evolutionary algorithms or optimization problems. Fitness values are used to evaluate and compare different genotypes within a population to determine which ones are more fit or well-suited for a given problem. In summary, genotype is the genetic code, phenotype is the observable characteristics resulting from that genetic code, and fitness value is a measure of how well a genotype performs in a specific defined context. These concepts are particularly important in fields like evolutionary science and genetic algorithms, where they play a crucial role in understanding and optimizing biological or computational processes. Here, the workflow includes setting up the design problem, analyzing the output results, and selecting the desired solution for the final output. It includes the ability to select and reconstruct any phenotype from the population after completing a simulation. From this, we can better understand an optimum condition based on environmental factors such as optimized heat gain for a facade or daylighting or wind conditions.

The distribution graphs show the fitness values that inform the final composition of tiles for the digital fabrication process. During the research, fitness values were employed for different layouts of tiles using the evolutionary algorithm, followed by a series of simulations, starting with a small set of solutions in the beginning, and moving toward a much higher value in the end. In this process, graphically, they start as red, meaning the initial generation had an extensive range, while the blue distribution is concentrated, meaning an optimal solution exists, and the algorithm finds it. In the parallel coordinate plot, the more optimal solutions in the later generations indicate that they work well for both fitness objectives. This means that our fitness goals are not contradictory, and there can be a solution that meets more than one requirement. In other words, we can make a sandpile composition from Voronoi points where we see the version best for sunlight and radiation and the best for an average condition. These were pulled from a large number of different evaluations. The studies for this paper are based on a relatively small number of hours and generations, between 100 and 500, but this can be increased to be much more.

Moving further, weather data from the UAE and sun trajectories were taken and entered into Wallacei with Grasshopper Ladybug. Around 500 hours were selected from the year when the conditions were very hot and involved high temperature, humidity, and low wind speed simultaneously. Here, we can study specific latitude and longitude for a certain location in the desert along with dry bulb temperature, dew point temperature, relative humidity, direct radiation, horizontal radiation, wind speed and wind direction. These can all be used to make decisions about the performance of a sand pile composition while also comparing the aesthetic. Dry bulb temperature was a specific concern due to the high temperature of the ambient desert air. The expectation is that the physical dune sand compositions created by the original Voronoi point grid may act as shading devices which can later be frozen with a binder to create a sand panel. The result is that the dune sand panels created for the study shaded up to 53% of the overall sunlight coming through in extremely hot times, creating enough evidence to continue the project and support the technology.

5. Conclusion

The research project asks how a regionally appropriate architectural system might be created from dune sand using a simple machine. It studies how the process can be optimized to become intelligent for a specific location and focuses exclusively on dune sand and the self-organization of sand piles as a generative process. To facilitate this line of inquiry, the research followed a process that was both analog and digital. The focus of this specific project was deemed important because desert dune sand is rarely used in modern construction. Cities in the Middle East and North Africa import massive quantities of river sand from Southeast Asia and Australia to fuel the need for concrete and masonry products.

The outcome is that an analog/digital workflow incorporating this bio-material can be combined with optimization to articulate specific architectural surfaces that have responses to local weather conditions. The research points to the fact that local dune sand material can be used to create one-to-one typological prototypes that resemble mashrabiya and jalis, offering a method for viable human-scale architectural prototypes to be further explored as an ongoing series. Further research can and should be done on the material responses to weather conditions, durability, and the structural limitations of the material.

This research is needed to continue conversations regarding how designers can replace current proprietary media in the desert, such as mass-produced masonry and concrete created from unsustainable methods using imported sand. The project responds to pressing global issues as identified by the following UN Sustainable Development Goals: SDG11, "Sustainable Cities and Communities" by helping to design resilient and sustainable cities and human settlements and designing material that aids in the reduction of environmental impacts of cities and city building by fostering resource efficiency in sustainable and resilient building processes; SDG12 by fostering responsible consumption and production in order to ensure sustainable consumption and production patterns, and to ensure good use of resources; SDG13, "Climate Action" by reducing greenhouse gases due to transportation and importation on a global scale (Beiser, 2016, UN, 2020)

The significance of sand as a resource is paramount, constituting one of the most extensively employed materials globally, second only to the elemental requisites of air and water. This material is ubiquitous in contemporary society, ranging from personal computers and glass, to concrete and asphalt road infrastructure. Nevertheless, it remains paradoxical that the preeminent repository of sand is primarily overlooked for desert construction. A critical imperative is thus underscored, comprehending the latent potential of desert sand and its applicability as a fundamental environmental concern, particularly for the regions intrinsically intertwined with this invaluable resource.

Given the ramifications of regional and global construction, it is apropos to explore this as an avenue for further scholarly investigation. Countries in the MENA region are emblematic of a locale reliance on predominantly imported materials or resources fashioned from foreign sources. Consequently, the imperative of harnessing indigenous resources and innovating novel architectural design paradigms utilizing local sand becomes a conduit to realizing transformative solutions in alignment with the United Nations Sustainable Development Goal for terrestrial ecosystems.

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This work is part of an ongoing research stream focused on the use of dune sand as a material strategy for local architecture in arid conditions.
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REVERSE ENGINEERING CONSTRUCTION INDUSTRY REALITIES: REPURPOSING STANDARDIZED LEFTOVER MATERIALS FOR DIGITAL FABRICATION

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Abstract. The paper investigates the appropriateness of computational design tools and affordable registration processes for repurposing standardized construction industry leftover materials of variable geometry for subtractive digital fabrication. Through the analysis and discussion of four case studies the authors propose discrete steps towards streamlining a workflow that can help reduce waste, promote sustainable practices and potentially create new revenue streams for the industry.

Keywords: *sustainability, architecture, computational design, digital fabrication*

ملخص. تبحث الورقة في مدى ملاءمة أدوات التصميم الحسابي وعمليات التسجيل لإعادة استخدام المواد المتبقية من صناعة البناء الموحدة ذات الهندسة المتغيرة للتصنيع الرقمي المطروح. من خلال تحليل ومناقشة أربع دراسات حالة ، يقترح المؤلفون خطوات منفصلة نحو تبسيط سير العمل الذي يمكن أن يساعد في تقليل النفايات وتعزيز الممارسات المستدامة وربما خلق تدفقات إيرادات جديدة للصناعة.

الكلمات المفتاحية: *الاستدامة ، العمارة ، التصميم الحسابي ، التصنيع الرقمي*

1. Introduction

While the construction industry is one of the largest contributors to the global economy, it also generates a significant amount of waste in the form of leftover standardized materials. Many such materials, industrially produced or processed, have the potential to be repurposed for digital fabrication, but the tedious processes of registering, tracing, nesting, and appropriating them for various CNC machinery can be time-consuming and costly, often resulting to their recycling or mere disposal. While recent developments in the space of digital fabrication research have established procedures for capturing and analysing the natural variation of non-standard materials to make use of their irregularity to create unique assemblies (MacDonald et al, 2019), this has not been the case with discarded standardized materials. Within the context of highlighting and improving sustainability in digital fabrication, this paper performs a qualitative analysis of a proposed workflow and prototyping outcomes and investigates the role of computational tools in streamlining processes for upcycling leftover standardized materials.

The authors discuss the fabrication part of four case studies involving different materials, capturing technologies and subtractive digital fabrication methods explored through a series of intensive postgraduate academic workshops. The workshops output involved a series of adaptive parametric models, outside of the scope of this paper, that were then analysed and streamlined for fabrication with the workflow presented. The materials include leftover sheet mild steel, discarded marble/stone parts from slabs, remaining sheet acrylic pieces, and recyclable corrugated cardboard boxes. All material used was considered industry waste and was procured for free. A comprehensive workflow including discrete steps is proposed and empirically evaluated by upcycling the above waste material to realise a series of large-scale component-based prototype structures presented in this paper.

In conclusion, the research supports that computational tools can contribute to repurposing standardized construction industry leftover materials of variable geometry for subtractive digital fabrication. By streamlining the tedious processes of capturing, tracing, nesting, and fabrication, the authors propose a workflow that can help reduce waste, promote sustainable practices and potentially create new revenue streams for the industry.

2. Case Studies

The four case studies presented below were developed during a series of intensive two-week workshops which are a formal requirement of a Postgraduate Programme (Master of Science) in Computational Design and Digital Fabrication at the University of Nicosia. The workshops were held during the FALL Semester, once a year, from 2019 – 2022. The educational brief revolved around repurposing standardized construction industry leftover material for CNC fabrication. Different material and fabrication equipment were pre-selected for every workshop. Students were requested to develop an understanding of the chosen materials, their possibilities and restrictions towards realizing a prototype using digital fabrication methods. Parallel brief requirements encouraged the use of computational design methods (such as panelisation or aggregation) or suggested specific structural or spatial arrangements (for example self-supported space enclosures). Custom workflows were created to address the challenges of the process from registering the material to utilizing it for digital fabrication. The research approach involved the application of computational tools for simulating complex geometric problems and streamlining the proposed workflows. A brief description of the four case studies and their details is presented in the following chapters.

2.1. METAHEDRA 2022 – RECYCLABLE CARDBOARD

The latest workshop, held in 2022, focused on 3D multi-component aggregations using folded cardboard components. Laser Cutting equipment was employed towards fabricating a large scale prototype utilizing the computational knowledge and skills acquired during the semester. Scrap cardboard was used as construction material to promote sustainable practices for digital fabrication. Computational tools and a LiDAR camera were implemented for scanning and registering unfolded recyclable cardboard boxes to become usable for digital fabrication.

The outcome, titled *meta*HEDRA, was generated by aggregating a unique polyhedral component to *grow* a self-supported, arch-like framework structure. 177 components were developed into load-bearing modules that could be digitally fabricated out of flat sheets of reclaimed cardboard and then folded in shape (Figure 1). Modules were connected using industrial grade, heavy-duty staples to form larger ring-component assemblies that could be vertically stacked and secured following the same method. Octagonal cardboard panels were temporarily placed inside each ring, in order to address the material´s deformation during assembly and to provide connectivity instructions. The modules were made using the available material; cardboard of 6mm and 3mm in thickness. The variability of material was accounted for in the design by using different tolerances depending on material thickness.

The prototype was constructed in three parts: the two legs of the arch (base) that were assembled in parallel and finally the connecting top part. The installation had a footprint of 4.4 m² and a height of 3.2 m. The prototype was erected and presented at the ARC 2023 end of year exhibition.

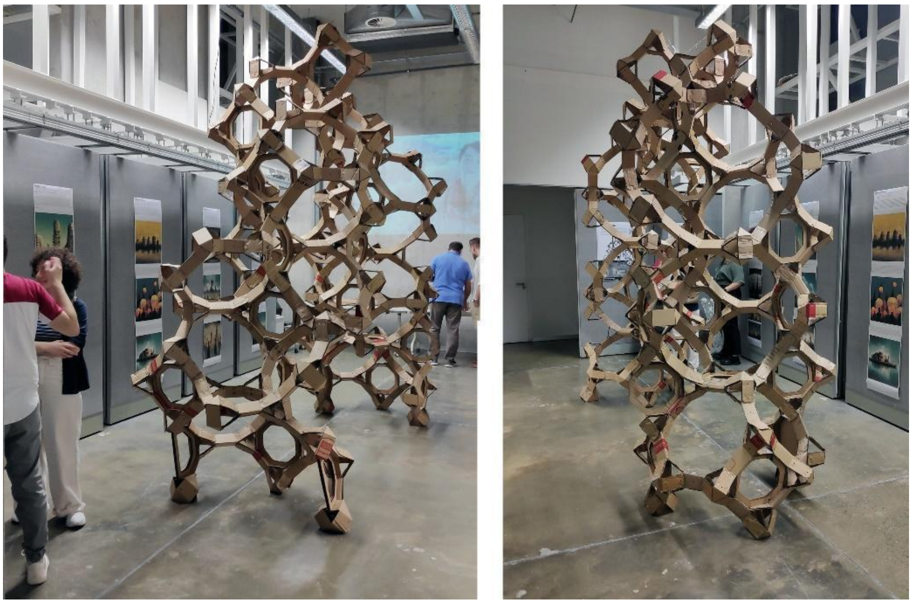

*Figure 1. meta*HEDRA 2022 at the ARC 2023 end of year exhibition

2.2. CHESSMAKE 2021– DISCARDED ACRYLIC

The workshop, held in FALL 2021, focused on 3D tessellations using sheet acrylic forming. Bending and Laser Cutting equipment were employed towards fabricating a series of large scale prototype structures utilising the knowledge and skills acquired during the semester. To promote sustainable practices for digital fabrication, scrap sheet acrylic was used as construction material. 3D scanning implementing LiDAR technology and Computational tools were implemented for scanning and registering leftover parts to become usable for digital fabrication.

The outcome of this workshop, titled CHESSmake, were life size, functional chess pieces. The structures were generated by tessellating 3D components on minimal surfaces. The students were divided in three teams, with each team designing a prototype with its own component, tessellation logic and assembly strategy. Each prototype consisted of 30 to 60 components that could be digitally fabricated out of flat sheets of acrylic and then bent using an acrylic bender to the final form. The components were made using white leftover acrylic at thickness of 3mm or 4mm. All structures were assembled in a puzzle-like-logic by the students during the workshop and the final prototypes had a footprint of 0.25 m² and a height of 1.25m. All chess pieces were presented and exhibited at the Architecture Research Centre at the University of Nicosia in 2021.

Figure 2. CHESSmake 2021, leftover acrylic registration setup

2.3. MABLE WEAVES 2020 – WASTE MARBLE

The workshop was held in FALL 2020 and focused on utilizing leftover marble parts, as the main construction material, to develop a series of design proposals. The workflow included 3D scanning implementing LiDAR technology for registering and documenting real-life objects to be used as input for computation and digital fabrication. Additionally, a 7-Axis CNC robot, customized for Marble and Stone forming, was utilized for experimentation with digital fabrication assignments.

The outcome of this workshop, titled Marble Weaves, were three prototypes utilising linear marble leftover pieces of variable length and standard thickness (20mm and 30mm) (Figure 2). Each prototype was limited to 100 pieces but the ideas were scalable. The notion of design tolerance presented a key element to be addressed and the participants devised innovative computational solutions to creatively incorporate the inherent variable material in their proposals. The proposals included an undulating wall cladding, a freestanding partition/divider and a decorative wall feature/3D lattice. Due to the pandemic, the prototypes were not realised but all teams have resolved their proposals, created mock-ups and prepared files for robotic fabrication.

Figure 3. MABLE WEAVES 2020, marble leftover pieces registration setup

2.4. X-MAX 2019 – LEFTOVER MILD AND GALVANISED STEEL

The workshop was held in FALL 2019 and utilized Scrap mild steel in sheet form as construction material to investigate and evaluate sustainable design and fabrication practices (Georgiou et al, 2021). Registering leftover steel parts as to be usable for digital fabrication presented an essential task that required computational focus. UAVs and orthophotography were implemented and computational tools were developed for automating and optimizing the workflows.

The outcome, titled X-MAX, was generated by populating a single, adaptable 3D component using puzzle-like logic to form an efficient self-supported doubly curved structure. 190 components were developed into load-bearing modules that could be digitally fabricated out of flat sheets of material and then CNC bent in shape using variable bent angles. (Figure 4). Modules were connected using bolts to form circular rings that could be vertically stacked and secured using the self-weight of each row. The modules were made using galvanized and mild steel of 2mm, 1.5mm and 1.0mm in thickens, and were arrayed forming an ascending pattern. The installation weighed 250 kg, its footprint ranged at 2.4m² and its height to 4m. All parts were assembled in a puzzle-like routine in 8 hours over a period of a day, by a team of ten students. The structure was donated to the Local Municipality and it is currently hosted as a public installation at the main square of the city.

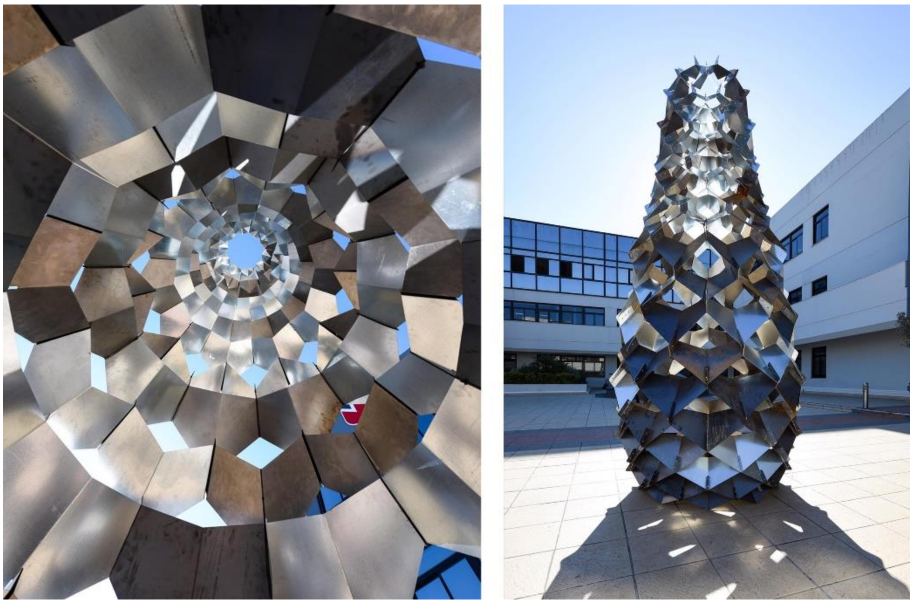

Figure 4. X-MAX 2019 at the University of Nicosia

3. Workflow

The workflow presented is approached, for the purposes of this research, as a stand-alone phase of the design process (Figure 5). During the course of analysing the four case studies for fabrication, four discrete steps have been identified where registering equipment and computational tools are applicable and can assist in streamlining the tedious efforts and processes involved.

The workflow begins with capturing accurate and detailed data of the leftover material. Orthophotography using Drones and Lidar cameras are implemented as affordable and efficient methods for capturing such data. The next step involves tracing the variable outline of the waste material ranging from rectangles often including slits and creases to complex shape off-cuts. For this part, purposely built tracing algorithms are implemented to extract the required data from raster images and point clouds. The following step involves arranging designed parts into the traced shapes, typically know as nesting. Computational tools are also implemented during this stage to streamline and optimize the process. The last step revolves around addressing challenges arising from using irregularly shaped parts or combining leftover material for digital fabrication using a laser cutter and a CNC router.

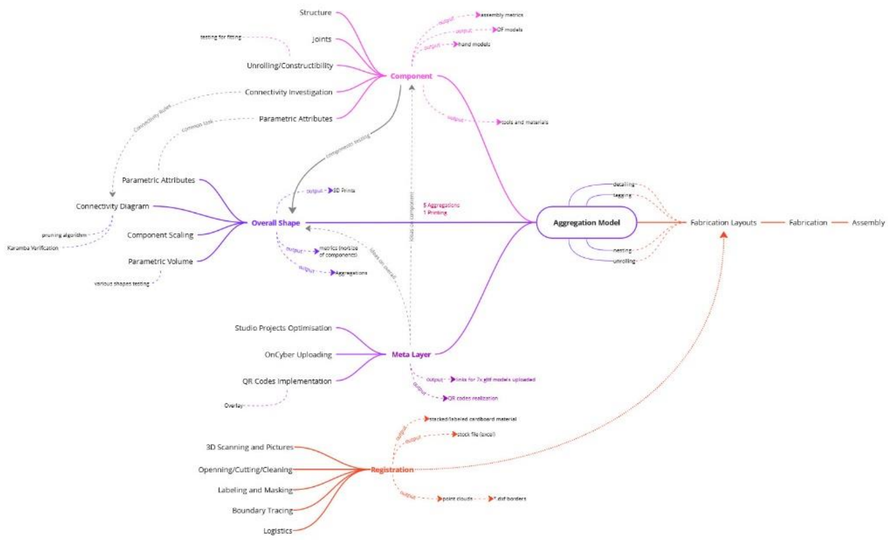

*Figure 5. meta*HEDRA process diagram

3.1. CAPTURING

Capturing and registering accurate and detailed data of the available material was an essential part to all four case studies, in order to be able to efficiently utilize all leftover and scrap pieces. The fact that the material palette came in a variety of shapes and sizes created a particular challenge for the research team. UAV Photogrammetry and Lidar scanning were explored as affordable and efficient methods for capturing such data, each of them being specific depending on the type of material used.

In the case of X-MAX, due to the larger, not easily transferred sheet metal material and its surface reflectivity making it inadequate to be 3d-scanned, the research team implemented a UAV photogrammetry approach. This approach involved capturing quality images, capable of later being translated into vector files with a high degree of precision. To minimize lens distortion, the UAV was mounted with a camera bearing a zoom lens (200 mm). The objects were placed on a rectangular base (green sheet) of known dimensions, in order to achieve a contrast between the sheet metal and its background. Markers were set on each corner and middle points of the outline of the rectangle with the use of a laser plane. Those were later used to further correct lens distortion through raster deformation techniques and assess the creation of an orthographic image. This method also incorporated large sheet numbering stickers to be clearly captured by the UAV.

Going forward with the latter case-studies, and since the material used was easier to handle and place in locations with controlled environments, the research team opted for using 3D scanning methods instead (Figure 6). The team used an experimental, tablet-mounted handheld lidar camera, Intel's L515 (Intel, 2023) and Dot3D (Dotproduct3D, 2023) scanning software. Despite 3D scanning being a more advanced method and fully digitized approach, the team faced a number of challenges bringing the capturing tasks forward. The particular Lidar camera used, is light sensitive and if used in an uncontrolled light environment it can generate undesirable effects due to scanning noise. 3D scanning is generally affected by material color and sheen, environmental light, reflectivity and shadows. In all three cases, contrasting background surfaces have been used to isolate the material from its surroundings and capture its dimensions more accurately. Depending on the captured material thickness, objects were placed in such distances between them in order to avoid interference from shadows casted by neighbouring objects.

Figure 6. Capturing recyclable corrugated cardboard boxes using a Lidar Camera

The marble material used in Marble Weaves had substantial thicknesses and lengths, varying from object to object, which was essential to be captured. In that particular case, the scanning team had to take care to reduce the shadows as much as possible by minimizing the light sources, ensuring these could be easily extracted from the point cloud during the post-processing stages. In the case of *meta*HEDRA, the cardboard material featured through-cuts that in most cases were too narrow to be captured accurately. The location of the slits was important to be mapped precisely as to increase the efficiency of the material usage during fabrication. To address this, the team used custom fabricated T-Section inserts that could be attached to the cuts, creating a wider and more visible area that could be easily captured and then removed from the scan during the post-processing.

3.2. TRACING AND REGISTRATION

Tracing and registering the outlines of the material ranging from rectangles, often including slits and creases, to complex shape off-cuts, required purposely built tracing algorithms. These algorithms differed when utilizing photogrammetry and raster images and evolved using the last three cases utilizing 3D scanning and point clouds.

In the case of X-MAX, where the capturing output was ortho-photographed raster images, the first step was an automated clean-up of the image files through a series of denoising and deblurring algorithms (Figures 7a and 7b). Normally the next step for the tracing of vector graphics would be to do a thresholding operation, where the image would be translated into a binary image (b&w), based on a brightness threshold (Davis et al, 1975).

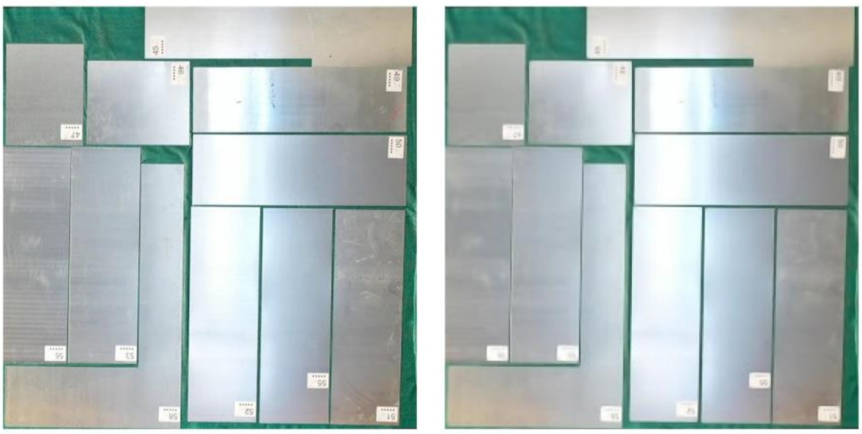

Figure 7. Orthophotography, a. unedited, b. with denoising and gaussian blur

However, since the design incorporated three different types of material with variable hue, a simple thresholding was found to create inaccuracies. For this reason, the implementation of an extra step of an edge detection algorithm was called for, in order to detect boundaries regardless of absolute brightness values. After a series of trial and error, the research team opted for a custom written “Sobel operator” (Sobel I., 2014) which gave results of maximum clarity (Figure 8).

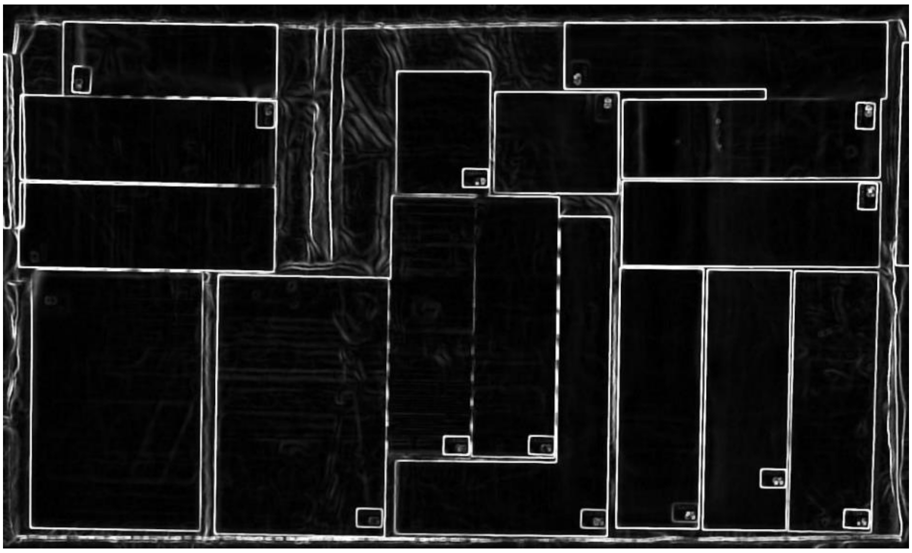

Figure 8. Edge detection enabled

The next step was the vector tracing of the treated images. To achieve this task, the team utilized an open source image tracing algorithm, called “Potrace”, for Rhinoceros 3d (Selinger P., 2003), (Bouteau G., 2018). The tracing algorithm is creating a spline at every boundary as detected by a threshold value, so, given the edge detection outcome, we ended up with a double outline, one for each side of the light-colored edge. The inner outline was selected, to increase the tolerance for nesting. The curves were then simplified and reduced, based on a set tolerance value. The traced outlines were then brought into scale through the known dimensions of the outline rectangle. The outcome was cross-referenced to several known dimensions in specific scrap parts, to ensure an overall deviation of less than 0.4%.

In a contrasting registering approach, starting with the Marble Weaves case study, where the output was a point-cloud, the aim was to isolate the captured elements and generate 2D and 3D wireframe geometry to be used as bounding areas for fabrication (Figure 9). The algorithms developed for this purpose, involved a voxel subsampling approach to reduce the size of the point clouds in order to become lighter to be handled computationally. A

Grasshopper 3D plugin, *Volvo*x (Zwierzycki, M. 2016), able to compute operations on Point Clouds was used for this purpose. The main part and aim of the registering algorithm was based on a color-coded isolation approach.

As discussed above, at the scanning phase, the objects were placed upon a high-contrast area. In order to isolate the objects from their background, the colour information from the point cloud was used. By translating the RGB coordinates into Cartesian vertices, the points were then split into colour groups based on distance based clustering, to create a point cloud posterization technique, of sorts. The background point groups were then removed. The remaining points were split into groups belonging to single objects via K-means clustering (Piech, C. 2023) (Figure 10). In order to lightly calculate the optimal plane for a bounding box of the point groups, the points were projected onto the ground plane and their convex hull was created and simplified to a rectangle. The longest side was used as the x coordinate, world z as y and their cross product as the z coordinate of the plane. Thus, the oriented bounding box for each object was calculated, alongside the overall dimensions of it.

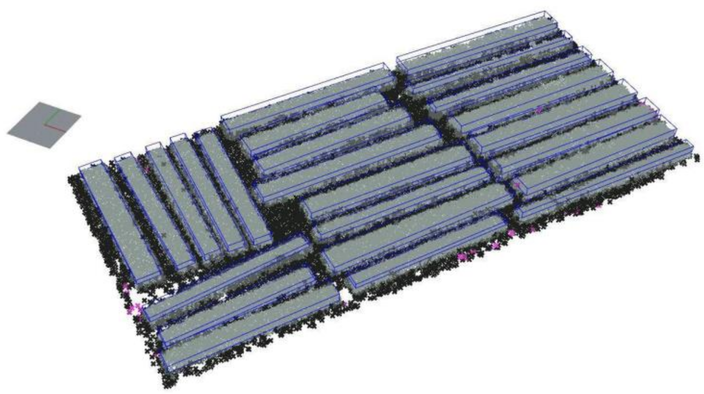

Figure 9. Bounding Wireframes on the scanned marble pieces - Marble Weaves

In the case of the Marble Weaves, where 3-dimensional objects had to be traced, self-cast shadows provided a 3d color group providing the thickness dimension.

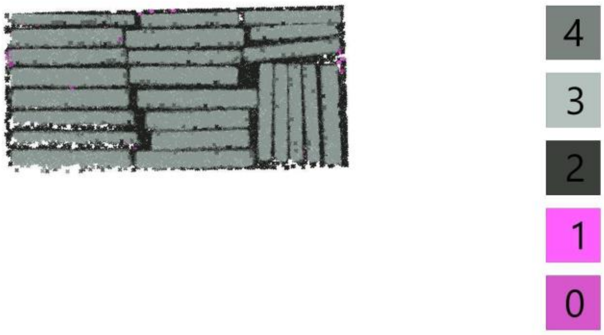

Figure 10. Color Groups and isolation of objects on Point Cloud

Even though the aforementioned algorithm was successful in its task, generating a rectangular bounding box for the scanned objects, it proved inadequate to tackle the complex shapes of the succeeding workshops, CHESSmake and *meta*HEDRA. It was therefore necessary to improve the algorithm in order to refine the point cloud and exclude any isolated points occurring by the 3d scanning noise. Specifically, K-means clustering was used to isolate points not belonging to the shape boundary in order to trace the irregular shapes of the scrap acrylic sheets used in the CHESSmake workshop. Similarly, in the case of the most recent workshop, *meta*HEDRA, we incorporated an additional shadow based colour group in combination with the point clustering to isolate and trace the cardboard cuts accurately.

3.3. NESTING

The next step was the fitting of the designed components onto the registered parts, so as to ensure reutilization of the available scrap material. This step involved arranging designed parts into the traced boundaries, typically known as nesting. The more efficient the arrangement the lower the material waste. Computational tools were also implemented during this stage in the workflow to streamline and optimize the process.

In the case of X-MAX, CHESSmake and *meta*HEDRA nesting in complex shapes was performed using OpenNest (Petras V., 2023), a 2D Polyline Packing plugin for grasshopper 3D. The designed shapes were automatically laid-out into the scanned/traced boundaries mentioned earlier. Whenever a boundary was filled and a shape could not be fit, it was routinely moved to the next boundary. A set number of rotations per item was assigned (24, every 15 degrees) as to reduce nesting times. The algorithm proved especially useful in the case of *meta*HEDRA, where complex layouts of parts were generated to avoid the cardboard slits and therefore increase material usage efficiency.

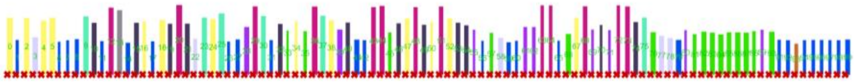

Figure 11. Marble Weaves - Linear Grouping

In the case of Marble Weaves the linear nature of the scrap material and the chosen fabrication method (drilling) has resulted in a different nesting approach. The marble pieces were initially sorted by length and then placed next to each other along the X axis (Figure 11). A sorted library of wanted part dimensions was cross-referenced to the available registered scrap material to ensure best overall fit. An identical arrangement was proposed for the fabrication layout.

3.4. COMPILING FOR FABRICATION

The last step revolves around addressing challenges arising from using irregularly shaped parts or combining leftover material for digital fabrication using a laser cutter and a CNC router.

For all cases the research team faced the issue of positioning the leftover pieces on the CNC machine bed. Especially for the case of CHESSmake and since the leftover pieces were irregular in shape a strategy was needed to correlate the physical item rotation with the digital part. An algorithm was used initially to define the optimum (smaller) bounding box within the border of the CNC table. Once a fit bounding box was defined for every leftover piece, they were marked, assigned a different colour and were superimposed with a common base point. The combined shapes were then printed in 1:1 scale using a plotter and were mounted on the laser bed. The laser operator was therefore able to place each leftover piece on its outline printed on the paper which corresponded to the file for fabrication. Usually the paper needed to be replaced after a number of iterations as it was becoming damaged by the laser cutter. The option of projecting onto the bed using a ceiling mounted projector instead of printing was also investigated and could be further developed/applied in future research. The cases of *meta*HEDRA and X-MAX were simpler and did not apply the above methodology as the cardboard and metal sheets material had rectangular dimensions so the research team could associate an axis (X or Y) of the digital boundary with the physical material.

Finally, for Marble Weaves, and as mentioned earlier, an arrangement based on sorting the pieces by length was proposed for the CNC table (Figure 12). The negative of the resulting shape was laser-cut out of polystyrene to secure the marble left-over pieces in places.

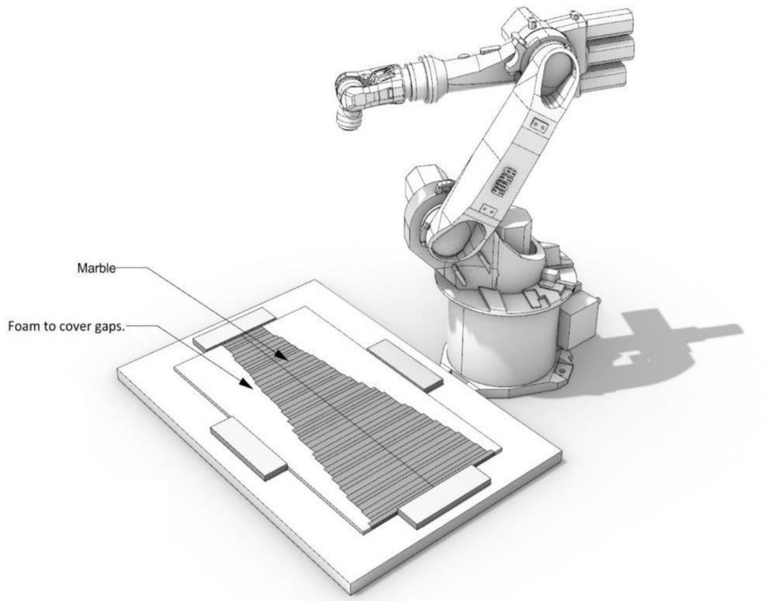

Figure 12. CNC Table Setup for Marble Weaves

4. Conclusion

The paper presented the outcome of four case studies focusing on the process of digitally capturing and registering leftover material, while appropriating it for digital fabrication. Standardized Materials such as sheet metal, acrylic sheets, marble slabs and corrugated cardboard were processed through a series of steps to enable the realisation of a series of design proposals. The process was driven by the waste material itself, in terms of scarcity, material properties, as well as available shapes and sizes. The experimental nature of the projects presented in the paper does not reflect the industry's typical case studies in a linear matter. The exaggerated forms and bespoke geometries used here, however, are aiming to act as an overly demanding, extreme scenario that may act as a proof of concept for the proposed workflows. While the workflow presented, was applied to create temporary structures, the material itself is industry rated, at least for specific applications or under appropriate treatments and coatings. As such the authors support that a step towards implementing the process for the construction industry is feasible but requires further research to enable larger scale applications (for example formworks, shadings, facades, claddings, etc).

In conclusion, the research supports that computational tools can contribute to repurposing standardized construction industry leftover materials of variable geometry for subtractive digital fabrication. By streamlining the tedious processes of capturing, tracing, nesting, and fabrication, the authors propose a workflow that can help reduce waste, promote sustainable practices and potentially create new revenue streams for the industry. Furthermore, by employing digital tools, the limitation and variability of available material now becomes a design driver leading to solutions that wouldn't be otherwise possible to achieve using conventional methods.

Acknowledgments

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3.A.

SMART CITIES AND BUILDINGS - I

THE HIERARCHICAL LOCATION-ALLOCATION MODEL FOR PRIMARY HEALTH CARE FACILITIES PLANNING

A selected case study in Amman

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Abstract. This study integrates a procedural approach to *Primary Health Care Facilities* (PHCFs) planning in Jordan, by combining *Public Facilities Urban Planning Principles and Guidelines* with a *Hierarchical Location Allocation Model* (HLAM) through the *Process of Systematic Urban Planning* suggested by *Chadwick* (1969) and *Lee* (1973). The objective of this study is to offer planners and decision makers a framework that can help them make decisions when selecting the locations for PHCFs. The study methodology is based on an analytical approach to analyse data, and then an experimental approach was employed to investigate the relations between the study variables to test the study hypothesis and to answer the key questions. The study highlights the healthcare system of Jordan, and it suggests PHCF planning standards. The study also highlights the principles of public facilities urban planning, and the use of models in urban planning particularly HLAM. Then, the study introduces "*HLAM Application*" as a study tool which was built particularly to solve HLAM for primary healthcare system of Jordan.The results indicate that PHCF planning in Jordan suffers from the low efficiency of the spatial distribution in conformity with the population density and the max distance to the nearest healthcare facility and does not fulfill the public facilities urban planning principles and the hierarchy system of PHCF adopted by the Ministry of Health.

Keywords: *GIS, Smart planning, Hierarchical location allocation model, Primary healthcare centers, Amman.*

ملخص. تقدم هذه الدراسة نهجًا إجرائيًا لتخطيط مرافق الرعاية الصحية الأولية في الأردن، من خلال الجمع بين إرشادات التخطيط العمراني للمرافق العامة ونموذج تخصيص الموقع الهرمي من خلال عملية التخطيط الحضري المنتظم التي اقترحها تشادويك (1969) ولي

(1973). ثم اختبرت الدراسة فاعلية هذا النهج من خلال تطبيقه على سيناريو واقعي في منطقة صويلح مع الأخذ في الاعتبار عوامل مثل الكثافة السكانية، وإمكانية الوصول، والبنية التحتية للرعاية الصحية القائمة. أظهرت النتائج التطبيق العملي والفوائد للنهج المقترح في تحسين توزيع مرافق الرعاية الصحية الأولية، مما يؤدي إلى تحسين الوصول إلى الرعاية الصحية وتقديم الخدمات. يساهم هذا البحث في رؤى قيمة في مجال تخطيط مرافق الرعاية الصحية ويقدم إرشادات عملية لصانعي القرار والمخططين في الأردن وخارجها.

الكلمات المفتاحية: *نظم المعلومات الجغرافية، التخطيط الذكي، نموذج تخصيص الموقع الهرمي، مراكز الرعاية الصحية الأولية، عمان.*

1. Introduction

Although often lauded for its advanced healthcare system in the Middle East, Jordan is not immune to a number of obstacles (WHO, 2006). One of these obstacles is the inadequate planning of Primary healthcare facilities (PHCFs), as their geographical distribution does not align with the population density - ultimately negatively impacting on the quality of healthcare delivery in the country.

The healthcare system, in Jordan consists of three types of healthcare facilities; Comprehensive Healthcare Centers (CHCs) Primary Healthcare Centers (PHCs) and Sub Healthcare Centers (Sub Cs). These facilities work together in a structure to provide levels of healthcare services (Bastani & Kazemzadeh 2009).

The objective of this study is to offer planners and decision makers a framework that can help them make decisions when selecting the locations for Primary Health Care Facilities (PHCFs). This framework will be useful in ways, such as refining site options identifying locations in new areas evaluating the effectiveness of previous location decisions improving existing location patterns within the hierarchical structure and ensuring fair distribution of customers based on facility capacity to prevent overcrowding or underutilization.

To achieve this goal the research combines a Hierarchical Location Allocation Model (HLAM) with a planning approach proposed by Chadwick (1969) and Lee (1973) integrating it with the planning standards, for Primary Health Care Facilities (PHCFs).

2. Mathematical Models in Planning

2.1 INTRODUCTION TO MATHEMATICAL MODELS

The utilization of mathematical models in urban planning has gained prominence since the mid-twentieth century. While models constitute a fractional facet of planning methodology, it is crucial to contextualize their significance within the broader scope of the planning process as a whole (Lee, 1973).

2.2 DEFINITIONS AND ORIGINS OF MODELS IN PLANNING

The fundamental concept underpinning the incorporation of models in planning is relatively straightforward. Consider a scenario where the creation of an intricate network of lines and pulleys is required to lift and relocate substantial weights from diverse points. In situations of high complexity, anticipating the consequences of altering a single line's position on the entire system can be challenging. To address this, the creation of a scale model with string might be undertaken, allowing for the formulation of optimal string-pulling patterns to achieve overarching objectives. Such a process enables the testing and refinement of actions in advance, thus informing the construction of the actual system (Lee, 1973).

2.3 APPLICATION OF MATHEMATICAL MODELS IN HEALTHCARE PLANNING

The realm of healthcare planning presents a fertile ground for the application of mathematical models. These models offer quantitative tools to analyze various aspects of healthcare systems, aiding in decision-making processes, resource allocation, and policy formulation. In the context of Jordan's healthcare system, mathematical models can be employed to assess the effectiveness of existing healthcare services, predict future healthcare needs based on demographic trends, and evaluate the impact of potential interventions.

2.4 INCORPORATING URBAN STANDARDS THROUGH MATHEMATICAL MODELING

One significant challenge within Jordan's healthcare landscape is the absence of urban healthcare standards. Mathematical models can play a pivotal role in addressing this issue by facilitating the formulation and implementation of standardized healthcare guidelines tailored to urban environments. By quantitatively analyzing factors such as population density, geographic distribution of facilities, and resource allocation, mathematical models can inform the development of comprehensive urban healthcare standards that ensure equitable access and consistent quality of care.

2.5 ENHANCING DECISION-MAKING THROUGH MATHEMATICAL ANALYSIS

Mathematical models also offer the potential to enhance decision-making processes in healthcare planning. By quantifying the potential outcomes of different scenarios, these models enable planners to evaluate the effectiveness and efficiency of various strategies. In the context of Jordan's healthcare system, mathematical analysis can assist in identifying optimal resource allocation strategies, prioritizing healthcare initiatives, and assessing the potential impact of policy changes.

2.5.1 Leveraging Data-Driven Intelligence for Enhanced Urban Healthcare

Mathematics and statistics enable precise distribution of resources, aligning medical personnel, equipment, and facilities with urban healthcare demands. Smart planning employs real-time data to allocate resources dynamically, ensuring efficient and effective healthcare provision.

Geographic Information Systems (GIS) coupled with mathematical modeling provide spatial insights. This aids optimal placement of healthcare facilities, ensuring equitable access across urban areas and addressing the absence of standardized urban healthcare guidelines.

Mathematics and statistics contribute to Decision Support Systems (DSS). These systems amalgamate data sources, model scenarios, and provide evidence-based recommendations, empowering urban healthcare planners to make informed choices and strategize effectively.

The synergy of mathematics, statistics, and smart planning holds promise for revolutionizing urban healthcare in Jordan. By leveraging data-driven intelligence, the nation's healthcare system can proactively address challenges, enhance accessibility, and elevate the overall quality of care for urban populations.

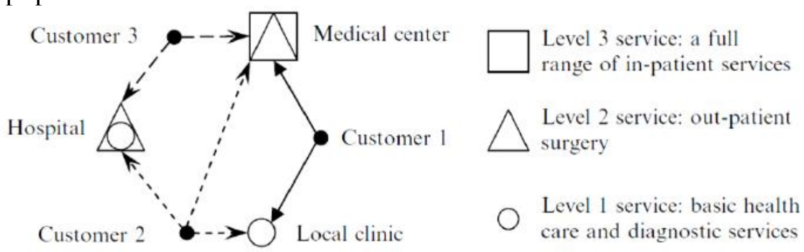

Figure 1: An Example of a Health Care Delivery System.
(Source: Bastani, 2009).

3. A Framework to Primary Health Care Facilities Planning in Jordan

3.1 HIERARCHY AND SPATIAL RELATIONSHIPS

The relationship between the three types of health care facilities – Sub-Cs, PHCs, and CHCs – is critical for the effective functioning of the healthcare system. By analyzing the Proposed Primary Health Care Criteria and Standards on the Jordan Map of Health (2008) and the Developed Standards, it is evident that the existence of Sub-centers is linked to PHC centers, and PHC centers are related to CHC centers. This relationship informs the necessity for a balanced distribution: every 2 or 3 Sub-C centers necessitate one PHC center, and every 3 or 4 PHC centers require one CHC center.

3.1.1 Formulation of Criteria for System Testing

The formulation of criteria for assessing the primary healthcare system's functioning is a crucial step in the planning process. This stage involves predicting the operating characteristics of each alternative configuration and evaluating the interactions between system variables. Building upon the concept of relationships between major activities, a location-oriented approach is adopted, aligning with the principles of the location-oriented models. Jordan's primary healthcare system is structured hierarchically, with CHC centers (P3) offering services across lower-level facilities (P2 and P1). This nested system ensures the provision of services at higher levels encompasses those at lower levels, adhering to classification schemes outlined by Schultz (1970) and Şahin (2007).

This flow pattern attribute aligns with the Multi-flow system concept, as proposed by the Şahin scheme (2007), and the integrated discipline framework, as articulated by the Narula scheme (1986). This dynamic system allows patients to initiate their healthcare journey at any level within the healthcare hierarchy. Subsequently, patients can receive referrals to both lower and higher levels based on the specific requirements of their health case. This approach ensures flexibility and adaptability within the primary healthcare system, accommodating diverse patient needs and optimizing care delivery.

This integrated discipline ensures that patients can receive care at the nearest facility, with referrals to higher or lower levels based on the case. The spatial configuration of Jordan's healthcare system follows a coherent structure, where lower-level service areas are subsets of higher-level service areas. This spatial coherence is fundamental to the objective of minimizing total distances when locating healthcare facilities. By applying a median model, the aim is to optimize facility placement based on the principles discussed in Chapter 3 and the suggested standards outlined in Chapter 2.

3.1.2 The system objectives

First, to minimize the distance between population centers and primary health care facilities; Second, is to ensure equitable distribution of the primary health care facilities among the population centers.

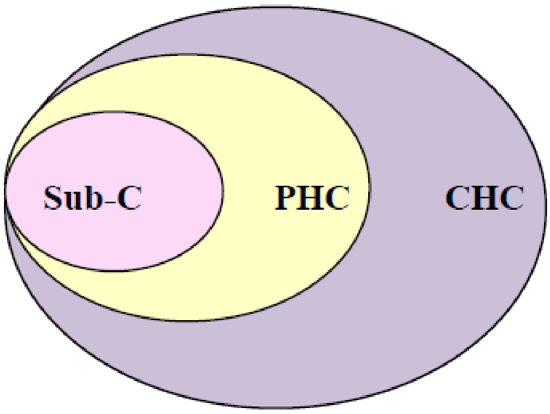

Figure 2. The Coherent Configuration Analysis of Primary Health Care System in Jordan. (Source: Author, 2013).

3.1.3 Model Assumptions

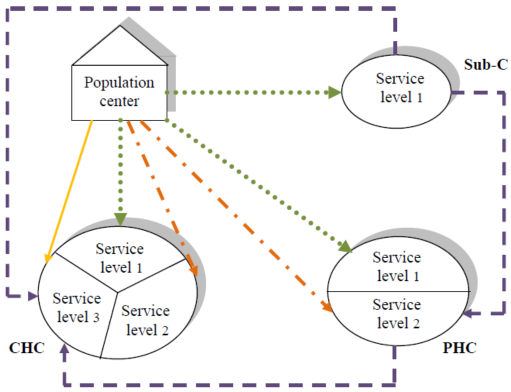

Figure 3. The Possible Flows between a Population Center and Sub-C, PHC, CHC and the Possible Referral Flow between Sub-C to PHC, and Sub-C to CHC and also PHC to CHC Analysis. (Source: Author, 2013)

Travel to healthcare facilities is determined by proximity, ensuring that patients access the nearest appropriate-level facility. Depending on the level of care required, patients are directed to Sub-C, PHC, or CHC centers. Patients seeking level 1 healthcare services have the option to visit Sub-C, PHC, or CHC centers, while those seeking level 2 services can choose between PHC and CHC centers. Patients in need of level 3 services exclusively visit CHC centers.

Referral mechanisms between Sub-C and PHC, as well as PHC and CHC, are factored into the system. The predetermined number of Sub-C, PHC, and CHC centers, along with their maximum capacity defined by planning standards, are key considerations. Importantly, simultaneous location of Sub-C, PHC, and CHC centers is required, and the model prohibits their co-location on the same site due to its successively inclusive nature. However, it's important to note that the model is primarily focused on operational efficiency and lacks consideration of broader social aspects.

3.1.4 Problem Formulation

While the study doesn't delve into model formulation, we conducted a preliminary analysis to identify a fitting Hierarchical Location-Allocation Model for Jordan's primary healthcare system, aligning with its objectives and assumptions. Despite various attempts in the literature to propose hierarchical location models, none effectively cater to Jordan's three-level primary healthcare system.

Thus, the study selected a formulation with similar objectives and assumptions, albeit representing a two-level hierarchy. We then adapted this chosen formulation to accommodate the three-level hierarchy system. The subsequent section presents the original formulation, its objectives, assumptions, and constraints. Following that, we explore the necessary adjustments to tailor it to Jordan's primary healthcare system. Additionally, the original formulation will be applied to the study's two-level hierarchy, focusing on specialized planning considerations.

3.2 THE SELECTED FORMULATION

The selected formulation (Şahin & Süral, 2007) represents a two-level, multi-flow, nested system, in which a population center at location i is provided either directly or via a **Type 1** facility for its **level 1** services and can be served by a **Type 2** facility for its both **level 1** and **level 2** services. The same model can be seen in Narula and Ogbu (1985).

3.2.1 Model Assumptions

Model assumptions are as follows:

1. The formulation represents a two-level, multi -flow, nested, coherent, and capacitated system;

2. The objective function is to minimize the total demand-weighted distance from demand sites to **Type1** and **Type2** facilities and referred demand weighted distance from **Type1** to **Type2** facilities;
3. The solution space is discrete and finite;
4. The number of facilities at each level is known (exogenous model).

3.2.2. Objective Function and its Constraints
The objective function of this model and its related constraints are as follows:

$$\boldsymbol{z = \sum_j \sum_k u_{jk} c_{jk} + \sum_i \sum_j v_{ij} c_{ij} + \sum_i \sum_k w_{ik} c_{ik}} \quad \textbf{(1)}$$

Subjected to:

$$\sum_j u_{jk} + \sum_i w_{ik} = d_k \quad \forall\, k \in K \quad \textbf{(2)}$$

$$\sum_i v_{ij} = \sum_k u_{jk} \quad \forall\, j \in J \quad \textbf{(3)}$$

$$\sum_k u_{jk} \leq M_j y_j \quad \forall\, j \in J \quad \textbf{(4)}$$

$$\sum_j v_{ij} + \sum_k w_{ik} \leq M_i x_i \quad \forall\, i \in I \quad \textbf{(5)}$$

$$\sum_j y_j = p \quad \textbf{(6)}$$

$$\sum_i x_i = q \quad \textbf{(7)}$$

$$u_{jk} \geq 0 \quad \forall\, j \in J \quad \forall\, k \in K \quad \textbf{(8)}$$

$$v_{ij} \geq 0 \quad \forall\, i \in I \quad \forall\, j \in J \quad \textbf{(9)}$$

$$w_{ik} \geq 0 \quad \forall\, i \in I \quad \forall\, k \in K \quad \textbf{(10)}$$

$$y_j \in \{0,1\} \quad \forall\, j \in J \quad \textbf{(11)}$$

$$x_i \in \{0,1\} \quad \forall\, i \in I \quad \textbf{(12)}$$

$$x_i + y_i \leq 1 \quad \forall i \in I \quad \textbf{(13)}$$

Where;

K the set of population centers or the set of demand sites $\{(\boldsymbol{x_k}, \boldsymbol{y_k})\}$;

J the set of candidate sites for **Type1** health facility $\{(\boldsymbol{x_j}, \boldsymbol{y_j})\}$;

$\boldsymbol{I}$ the set of candidate sites for **Type2** health facility $\{(\boldsymbol{x_i}, \boldsymbol{y_i})\}$;

$\boldsymbol{u_{jk}}$ Population at site $\boldsymbol{k}$ assigned to a **Type1** health facility at site $\boldsymbol{j}$;

$\boldsymbol{v_{ij}}$ Number of referral cases between a **Type1** health facility at site $\boldsymbol{j}$ and a **Type2** health facility at site $\boldsymbol{i}$;

$\boldsymbol{w_{ik}}$ Population at site $\boldsymbol{k}$ assigned to a **Type2** health facility at site $\boldsymbol{i}$;

$\boldsymbol{c_{jk}}$ Distance between a population center at site $\boldsymbol{k}$ and a **Type1** health facility at site $\boldsymbol{j}$;

$\boldsymbol{c_{ij}}$ Distance between a **Type1** health facility at site $\boldsymbol{j}$ and a **Type2** health facility at site $\boldsymbol{i}$;

$\boldsymbol{c_{ik}}$ Distance between a **Type2** health facility at site $\boldsymbol{i}$ and a population center at site $\boldsymbol{k}$;

$\boldsymbol{M_j}$ Is the capacity of **Type1** health facility at site $\boldsymbol{j}$;

$\boldsymbol{M_i}$ Is the capacity of **Type2** health facility at site $\boldsymbol{i}$;

$\boldsymbol{p}$ The predetermined number of **Type1** facility to be located;

$\boldsymbol{q}$ The predetermined number of **Type1** facility to be located;

$\boldsymbol{d_k}$ The total population.

3.2.3. Model Development

Lee (1973) offers a useful model-formulation approach. Selecting relevant variables and relationships is key, guided by the problem's definition. The model should accurately represent the targeted phenomena.

Therefore, the study needs to develop the selected model by adding new variables and relations to include or cover the third level of hierarchy.

Returning to the model objectives and assumptions related to the primary health care system of Jordan and Figure 4 mentioned previously. The study can proceed the following:

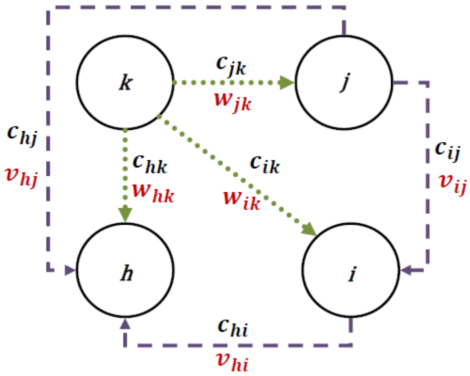

Figure 4. The Possible Flows between k, j, i, and h (Source: Author, 2013.)

Consider four sets: K, J, I, and H, representing population centers, candidate sites for Sub-C, PHC, and CHC, respectively. Potential flows between these sites are outlined as follows: a patient from a population center (k) may go to a Sub-C (j) for level 1 services, or to a PHC (i) for level 1 or/and level 2 services, or to a CHC (h) for level 1 or/and level 2 or/and level 3 services based on health needs or proximity. Additionally, scenarios arise where a patient directed to Sub-C (j) might need referral to a PHC (i) or directly to a CHC (h). Similarly, a patient initially directed to a PHC (i) could require referral to a CHC (h). These complex patient flow dynamics must be considered in optimizing healthcare services.

The chosen model primarily involves three potential flows: from a population center to a Type1 facility, to a Type2 facility, or as a referral between the two types. This model encapsulates the intricate flow dynamics within Jordan's primary healthcare system, aligning with health system objectives and assumptions. Thus, the model is formulated as follows:

$$A = \sum_j \sum_k w_{jk} c_{jk} + \sum_i \sum_k w_{ik} c_{ik} + \sum_h \sum_k w_{hk} c_{hk} + \sum_i \sum_j v_{ij} c_{ij} +$$

$$hivhichi + hjvhjchj \qquad (1)$$

Subjected to;

$$\sum_j w_{jk} + \sum_i w_{ik} + \sum_h w_{hk} = w_k \quad \forall\, k \in K \tag{2}$$

$$\sum_i v_{ij} = \sum_k w_{jk} \quad \forall\, j \in J \tag{3}$$

$$\sum_h v_{hj} = \sum_k w_{jk} \quad \forall\, j \in J \tag{4}$$

$$\sum_h v_{hi} = \sum_i w_{ik} + \sum_i v_{ij} \quad \forall\, j \in J \tag{5}$$

$$\sum_k w_{jk} \le M_j \quad \forall\, j \in J \tag{6}$$

$$\sum_j v_{ij} + \sum_k w_{ik} \le M_i \quad \forall\, i \in I \tag{7}$$

$$\sum_k w_{hk} + \sum_k v_{hj} + \sum_k v_{hi} \le M_h \quad \forall\, i \in I \tag{8}$$

$$\sum_j y_j = p \tag{9}$$

$$\sum_i x_i = q \tag{10}$$

$$\sum_h z_h = s \tag{11}$$

$$w_{jk} \ge 0 \quad \forall\, j \in J \quad \forall\, k \in K \tag{12}$$

$$w_{ik} \ge 0 \quad \forall\, i \in I \quad \forall\, k \in K \tag{13}$$

$$w_{hk} \ge 0 \quad \forall\, h \in H \quad \forall\, k \in K \tag{14}$$

$$v_{ij} \ge 0 \quad \forall\, i \in I \quad \forall\, j \in J \tag{15}$$

$$v_{ih} \ge 0 \quad \forall\, i \in I \quad \forall\, h \in H \tag{16}$$

$$v_{hj} \ge 0 \quad \forall\, h \in H \quad \forall\, j \in J \tag{17}$$

$$y_j \in \{0,1\} \quad \forall\, j \in J \tag{18}$$

$$x_i \in \{0,1\} \quad \forall\, i \in I \tag{19}$$

$$z_h \in \{0,1\} \quad \forall\, h \in H \tag{20}$$

$$x_i + y_i + z_i \le 1 \quad \forall i \in I \tag{21}$$

$$y_j + z_j \le 1 \quad \forall j \in J \tag{22}$$

Where;

$\boldsymbol{K}$ the set of population centers in determined area $\{(\boldsymbol{x_k}, \boldsymbol{y_k})\}$;

$\boldsymbol{J}$ the set of candidate sites for **Sub-C** health centers $\{(\boldsymbol{x_j}, \boldsymbol{y_j})\}$;

$\boldsymbol{I}$ the set of candidate sites for **PHC** health centers $\{(\boldsymbol{x_i}, \boldsymbol{y_i})\}$;

$\boldsymbol{H}$ the set of candidate sites for **CHC** health centers $\{(\boldsymbol{x_h}, \boldsymbol{y_h})\}$;

$\boldsymbol{w_{jk}}$ Number of people at site $\boldsymbol{k}$ who are assigned to a **Sub-C** health center at site $\boldsymbol{j}$;

$\boldsymbol{w_{ik}}$ Number of people at site $\boldsymbol{k}$ who are assigned to a **PHC** health center at site $\boldsymbol{i}$;

$\boldsymbol{w_{hk}}$ Number of people at site $\boldsymbol{k}$ who are assigned to a **CHC** health center at site $\boldsymbol{h}$;

$\boldsymbol{v_{ij}}$ Number of referral cases between a **Sub**-C health center at site $\boldsymbol{j}$ and a **PHC** health center at site $\boldsymbol{i}$;

$\boldsymbol{v_{hj}}$ Number of referral cases between a **Sub**-C health center at site $\boldsymbol{j}$ and a **CHC** health center at site $\boldsymbol{h}$;

$\boldsymbol{v_{hi}}$ Number of referral cases between a **PHC** health center at site $\boldsymbol{i}$ and a **CHC** health center at site $\boldsymbol{h}$;

$\boldsymbol{c_{jk}}$ Distance between a population center at site $\boldsymbol{k}$ and a **Sub-C** health center at site $\boldsymbol{j}$;

c_{ik} Distance between a population center at site k and a **PHC** health center at site i;

c_{hk} Distance between a population center at site k and a **CHC** health center at site h;

c_{ij} Distance between a **Sub-C** health center at site j and a **PHC** health center at site i;

c_{hj} Distance between a **Sub-C** health center at site j and a **CHC** health center at site h;

c_{hi} Distance between a **PHC** health center at site i and a **CHC** health center at site h;

M_j Is the maximum capacity of **Sub-C** health center at site j;

M_i Is the maximum capacity of **PHC** health center at site i;

M_h Is the maximum capacity of **CHC** health center at site h;

p The predetermined number of **Sub-C** health centers to be located in the area;

q The predetermined number of **PHC** health centers to be located in the area;

s The predetermined number of **CHC** health centers to be located in the area;

W The total population at the area;

The primary objective of function (1) is to minimize total distances between population centers and health centers (Sub-C, PHC, CHC), as well as referred distances between centers. Constraints (2) ensure equivalent assignment of people to health centers as the total population. Constraints (3) equate patients referred to PHC centers from Sub-C centers with the total PHC demand. Similarly, Constraints (4) and (5) relate to CHC centers. Constraints (6)-(8) handle facility capacities, while Constraints (9)-(11) determine the number of required Sub-C, PHC, and CHC centers. Constraints (12)-(17) pertain to non-negativity and integrality, while (18)-(22) prevent different health facilities of distinct types from being co-located to enforce a nested hierarchy.

3.3 DESIGN A STUDY TOOL

Addressing the query of how the Hierarchical Location-Allocation Model can be resolved, this research takes an action-oriented approach to integrate a procedural method into primary healthcare facility planning. (عليان,2001). To this end, a specialized application (software) has been devised, tailored to solve the model. Crafted using the alternating heuristic algorithm, the application is coded in Microsoft Visual Studio, aiming to provide a practical and user-friendly tool for planners and decision-makers. This application serves to operationalize the hierarchical location model, facilitating hypothesis testing. It processes input data corresponding to the 2-level and 3-level criteria equations and their associated constraints, with the accuracy of output data contingent on precise input information. A comprehensive analysis of input data is further discussed in the subsequent section.

3.3.1 The HLAM Application Properties

The designed software boasts the following characteristics and advantages:

1. The application solves the chosen HLAM, addressing both the 2-level hierarchy criteria and the developed 3-level hierarchy criteria to achieve set objectives and assumptions.
2. Organized into five tabs or divisions—Area Input Data, Evaluate 2-level Hierarchy Planning, Evaluate 3-level Hierarchy Planning, Optimal Sites for 2-Level Hierarchy, and Optimal Sites for 3-Level Hierarchy.
3. The first tab, "Area Input Data," accommodates essential input data divided into four tables: Population Centers, Sub-Cs, PHCs, and CHCs. Data includes:
   a. Population center locations. $\boldsymbol{K} = \{(\boldsymbol{x_k}, \boldsymbol{y_k})\}$
   b. Number of people assigned to each population center ($\boldsymbol{w_k}$).
   c. Sub-C center locations. $\boldsymbol{J} = \{(\boldsymbol{x_j}, \boldsymbol{y_j})\}$

d. PHC center locations. $\boldsymbol{I} = \{(\boldsymbol{x_i}, \boldsymbol{y_i})\}$
e. CHC center locations. $\boldsymbol{H} = \{(\boldsymbol{x_h}, \boldsymbol{y_h})\}$.

4. The second tab, "Evaluate 2-level Hierarchy Planning," assesses existing planning for a specific area using the 2-level hierarchy criteria (Figure 4). It aids planners and decision-makers in evaluating past location choices, avoiding facility overload or underuse. Data on primary health care planning (PHCF) standards is needed, including:
   a. Maximum capacity (catchment population size) of each center.
   b. Catchment area range (km) of each center.
   It's noteworthy that the application can assess planning for one facility level type (Location Allocation Model) if the study area has only one type of health care center, by entering data in the relevant field using this tab.
5. The third tab, "Evaluate 3-level Hierarchy Planning," mirrors the second but focuses on the 3-level hierarchy criteria.

6. The fourth tab, "Optimal Sites for 2-Level Hierarchy," identifies optimal health center sites for 2-level hierarchy criteria. It aids planners and decision-makers in refining current planning, enhancing existing location patterns, or establishing new facilities. Data pertaining to PHCF standards is necessary:
   a. Required number of each health center type.
7. The fifth tab, "Optimal Sites for 3-Level Hierarchy," resembles the fourth, addressing 3-level hierarchy criteria.

Visual diagrams accompany the last four tabs, using dots and lines to illustrate input data and results, offering a vivid overview of operations. GIS software is then employed to depict study area planning site maps. Further analysis of the integrated approach follows in the next section, "The Implementation and Monitoring Procedures."

3.4 THE IMPLEMENTATION AND MONITORING PROCEDURES

The procedure entails several steps for comprehensive analysis and optimization of primary health care facilities (PHCF) planning in a study area.

First, the study area is scrutinized by identifying its boundaries and subdivisions, analyzing network routes, public transport stops, land use planning, and topography. The aim is to understand the geographical context and distribution of population centers.

Second, population centers are defined and analyzed in terms of location and population size. The centroids of populated zones serve as demand points, with x and y coordinates determined using GIS ArcMap's "Calculate

Geometry tool." This data is then entered into the software's "Area Input Data" tab.

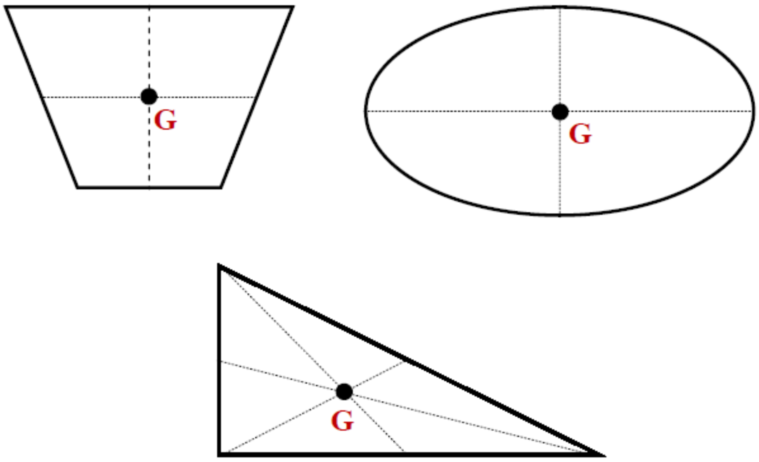

Figure 5. Centroid Point **(G)** for Some Different Shapes.
(Source: The Author, 2013)

Third, PHCF planning standards are applied to ascertain existing facilities' adequacy. This involves dividing the total population by the catchment population of health care centers, enabling estimation of required facilities.

Fourth, the current planning is evaluated using the Hierarchical Location-Allocation Model (HLAM) Application. Existing facilities' location, type, and capacity are entered, and the software assesses the allocation's effectiveness, highlighting areas of potential concern.

Fifth, proposed sites for health care centers are identified, considering planners' and decision-makers' input. The HLAM assists in optimizing potential solutions when numerous possibilities exist.

Sixth, optimal sites for health centers are determined using the HLAM Application. Proposed center locations are entered, and the software calculates the best sites based on model assumptions and objectives. This aids in selecting sites that improve existing facilities' placement and minimize overload.

Seventh, results are discussed and evaluated to determine the effectiveness of PHCF planning in the study area. Different solutions are developed if needed, assessing the selected optimal sites against 2-level and 3-level criteria.

Throughout these steps, the HLAM Application serves as a crucial decision-aid tool, helping planners and decision-makers optimize PHCF planning, allocate resources effectively, and improve health care accessibility.

4. A Case Study of Amman City

Amman, the primary capital city of Jordan, encompasses an area of approximately 7579 km2 and is home to over 2.5 million people across twenty-eight administrative districts. The city's population density was notably high in 2011, averaging 319.2 individuals per square kilometer, with concentrated pockets in central districts like Al-Yarmouk, Basman, Badr, Ras Al-A'ain, and Al-Madina.

4.1 THE STUDY AREA

4.1.1 Selection Criteria

The selection of the study area was guided by specific criteria to ensure a comprehensive evaluation of the integrated approach for (PHCF) planning. Al-Jubeiha was excluded due to its lack of PHCF, while areas with high and low populations such as Basman, Al-Yarmouk, Al-Qwasmah, Badr, Badr Al-Jadedah, Shafa Badran, and Uhod were excluded to facilitate study procedures. Additionally, districts with concentrated PHCF like Al-Madina, Al-Abdali, Zahran, and Ras Al-Aian were excluded, as well as those with a single type of health care center. Sweilih was chosen for 2-level criteria due to its lack of facilities and compact urban structure.

4.1.2 The Study Area of Sweilih District

Sweilih district is situated in the northwest of Amman and is comprised of ten neighborhoods. With a population of 71,200 and covering an area of 24.23 km2, Sweilih district has a population density of 2939 people per square kilometer (Table 1).

TABLE 1. Sweilih Neighborhoods in Terms of Area and Population.

Neighborhood	Population*	Area km^2
Al-Kamalyah	17893	2.63
Al-Hae Al-Sharqi	16587	1.59
Al-Fadelah	15000	1.35
Al-Rahmaniyah	8000	3.94
Maysaloon	6500	1.06
Al-Basha'ir	4000	2.54
Daboq	1700	3.24
Al-Furousiyah	650	2.14
Hadai'q Al-Husein	500	1.54
Al-Humar	370	4.20
Total	**71200**	**24.23**

(Source: GAM/ GIS Department, 2013).

* Estimated population of 2008.

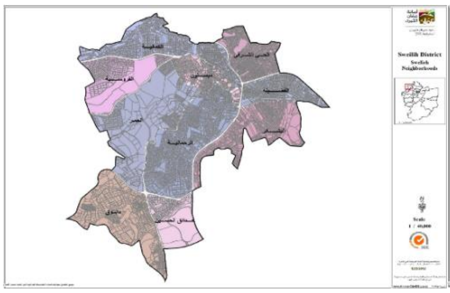

Figure 6. The Neighborhoods of Sweilih District Plan "Analyze the study area subdivisions". (Source: GAM /GIS Department Shapefile edited by Author, 2013).

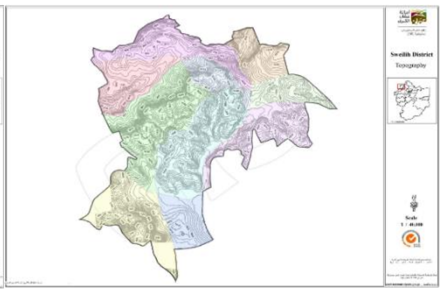

Figure 7. Sweilih Network Routs and Bus Stops Plan. (Source: GAM /GIS Department Shapefile edited by Author, 2013).

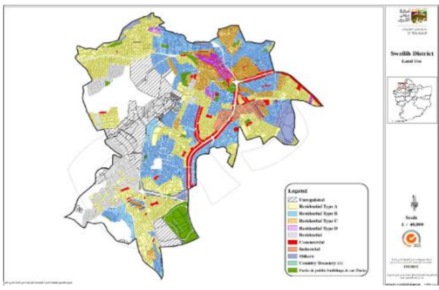

Figure 8. Sweilih Topographic Plan. (Source: GAM /GIS Department Shapefile edited by Author, 2013).

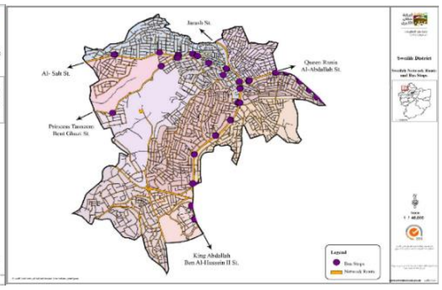

Figure 9. Sweilih Land Use Plan. (Source: GAM /GIS Department Shapefile edited by Author, 2013).

Sweilih district is well-connected through major network routes, linking it with neighboring areas such as Al-Jubeiha, Tla Al-Ali, Wadi Al-Seer, Um-Summaq, Khalda, Irbid Governorate, and Al-Balqa Governorate. Public transportation is accessible and serves the district and these connecting regions. The district exhibits a diverse land use pattern, featuring commercial and industrial zones, a satellite station, TV transmitter station, Royal Palaces, schools, parks, mosques, and various public and private facilities including health care centers (Figure 7 and Figure 8). The elevation in Sweilih varies, ranging from 900 meters to 1090 meters above sea level (Figure 9). Populated areas within Sweilih encompass a range of land use patterns, with exceptions for unregulated areas, including the Royal Palaces, King Abdallah Ben Al-Hussein II Park, and the satellite station (Figure 10).

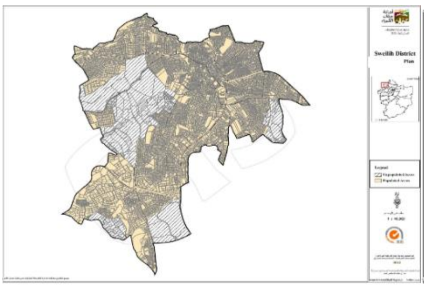

Figure 10. Sweilih Populated and Unpopulated Areas Plan. (Source: GAM /GIS Department Shapefile edited by Author, 2013).

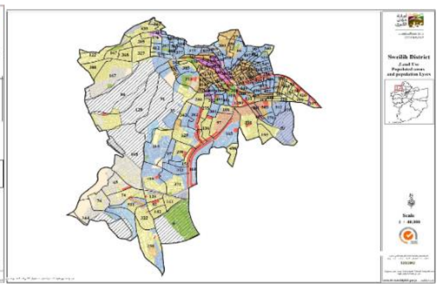

Figure 11. Prepare an Analysis of Population Centers based on Census 2004 Provided by GIS Database. (Source: GAM /GIS Department Shapefile edited by Author, 2013).

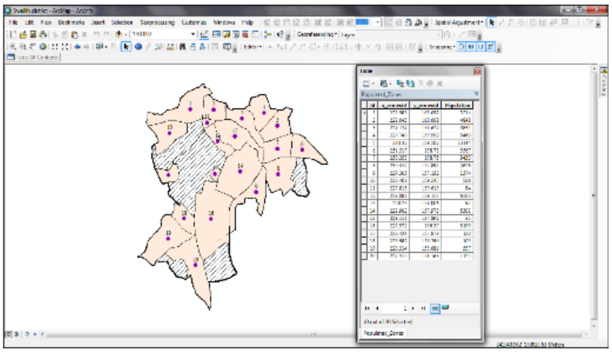

Figure 12. Sweilih Populated Zones Plan showing the Population Centers of Each Zone. (Source: GAM /GIS Department Shapefile edited by Author, 2013).

TABLE 2. The Attribute Table that has been exported to Microsoft Office Excel Software. (Source: The Author, 2013).

Poulation center ID	x_centroid	y_centroid	Population
1	226.9810028	160.0919952	3214
2	228.0429993	160.0679932	4848
3	229.173996	159.621994	9831
4	229.7489929	159.9920044	3460
5	230.3200073	159.5019989	13144
6	231.3170013	158.7100067	5567
7	230.3529968	158.75	9433
8	230.4519958	157.8910065	2626
9	229.3650055	157.1320038	1374
10	226.4080048	159.246994	566
11	227.8130035	159.6150055	84
12	228.8809967	159.151001	6500
13	228.2299957	159.0059967	91
14	228.9620056	157.9730072	5301
15	228.1109924	157.8919983	55
16	227.9720001	156.3699951	3199
17	226.4360046	157.878006	120
18	226.9819946	156.3959961	105
19	226.3139954	155.6860046	557
20	227.3150024	154.7630005	1125
			71200

The second step involves preparing an analysis of the population centers within the study area. To identify population centers within Sweilih district, each populated zone, comprising several residential blocks, is treated as a single population center. This involves determining the centroid of each populated zone, which is achieved through the use of the "Calculate Geometry" tool in GIS ArcMap 10 (Figure 12). The determination of populated zones is guided by neighborhood borders, main roads within neighborhoods, and residential unit types. The computed centroids serve as demand points or population centers for the Hierarchical Location-Allocation Model (HLAM). The x and y coordinates of these centroids are integrated and documented in an Attribute Table in GIS ArcMap 10, then transferred to

Microsoft Office Excel for consolidation. This data is subsequently imported into the HLAM Application, where it contributes to the evaluation and enhancement of the current primary health care facility planning within Sweilih district (Figure 12).

Figure 12 illustrates Sweilih's populated zones along with their corresponding centroid points, generated through GIS ArcMap. Each centroid point is associated with an "Id number," "x-centroid," "y-centroid," and population count. These data are systematically organized within a pre-arranged Attribute Table within GIS ArcMap. Subsequently, the "Export" tool in GIS ArcMap was employed to transfer this Attribute Table data to Microsoft Office Excel, where all Sweilih district information is consolidated into a single Excel sheet, as depicted in Table 2.

Next, the third step focuses on applying PHCF planning standards and principles. The application of Primary Health Care Facilities (PHCF) planning standards and principles is undertaken to ascertain the necessary types and numbers of healthcare facilities for Sweilih district. Given its compact urban layout without scattered population areas, the district boasts excellent accessibility via various transportation routes and public transportation options (Figure 12). Consequently, the required PHCF types for Sweilih are limited to Primary Healthcare Centers (PHCs) and Comprehensive Healthcare Centers (CHCs). To determine the specific quantities of these health centers needed to cater to Sweilih's population, the study divides the district's total population by the catchment population size for each required type.

$$\textbf{The number of required PHCs} = \frac{\mathbf{71200}}{\mathbf{20000}}$$

$$= \mathbf{3.56} \approx \mathbf{4}\ \textbf{Facilities}$$

$$\textbf{The number of required CHCs} = \frac{\mathbf{71200}}{\mathbf{60000}}$$

$$= \mathbf{1.18} \approx \mathbf{1}\ \textbf{Facility}$$

By applying PHCF planning the study concluded, that Sweilih district needs to add more three PHC facilities to adequate the needs of Sweilih citizens to primary health care services. The following table shows the shortfalls of PHCF at Sweilih district.

TABLE 3. The Shortfalls of PHCF at Sweilih District

Type of PHCF	Existing PHCF*	Required PHCF**	Shortfalls PHCF**
Primary Healthcare Centers (PHCs)	1	4	3
Comprehensive Healthcare Centers (CHCs)	1	1	0

5. Conclusions and recommendations

5.1 CONCLUSIONS

The study successfully achieved its main aim by integrating Public Facilities Planning Principles and Guidelines with the HLAM to formulate an integrated approach for PHCFs planning in Jordan. This approach was implemented through seven sequential procedures, demonstrating its effectiveness in analyzing and improving the distribution of health care facilities. By applying this integrated approach to the study areas of Sweilih district, the study showcased how it could evaluate past location decisions, determine optimal sites, and enhance existing location patterns based on hierarchical systems. Furthermore, the study developed PHCFs planning standards and highlighted the challenges and limitations of the current system, leading to recommendations for more effective and efficient planning in the future. The study's systematic methodology and HLAM application provide valuable tools for decision-makers and planners to enhance the spatial distribution and accessibility of PHCF services in urban areas.

5.2 RECOMMENDATIONS

Upon evaluating the study's findings, several key recommendations emerge for urban planners and decision-makers. It is crucial to conduct comprehensive studies regarding population distribution and minimize distances to PHCFs, while integrating hierarchy relationships and principles of public facilities planning. The study's systematic approach offers a potential remedy for the unequal distribution of healthcare facilities and medical staff in Jordan, aligning with the 2009 report by the Jordanian Civil Service Bureau and MOH. Urgent establishment of MOH planning standards for primary health care facilities is necessary to ensure transparency and fairness, mitigating nepotism and favoritism. Furthermore, the creation of a dedicated urban planning department within MOH is essential to oversee healthcare facility planning and enhance collaboration with municipalities. A centralized national database with consistent spatial information on health care facilities and population center locations is imperative for informed decision-making across government departments. Strengthening public transportation systems is vital for supporting CHC planning and accessibility. Implementing the study's integrated approach in other areas could yield additional recommendations for evaluating and enhancing current PHCF planning. Lastly, creating pedestrian-friendly environments at the neighborhood level is pivotal to ensuring easy access to public facilities within or near each community.

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USING GEOGRAPHIC INFORMATION SYSTEMS (GIS) TO LOCATE NEIGHBORHOOD PARKS BASED ON THEIR CATCHMENT AREA

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Abstract. The city of Amman suffers from a shortage of open spaces and parks, which are vital for increasing physical exercise, boosting the quality of life in a community, and stimulating social interaction. This problem draws attention to the absence of planning criteria in addition to the poor regulatory framework for the distribution and location selection of open spaces and parks and their proportions that are commensurate with the population of Amman, a critical issue that requires immediate planning solutions. This study focuses on using geographic information systems (GIS) to determine the optimal neighborhood park locations in Bader, one of Amman's districts, and collects data from specific documents about neighborhood parks, examples of guidelines, and criteria for distributing parks in different countries to determine the criteria and catchment area of neighborhood parks. Using ArcGIS 10.1's Network Analyst Tool and its applications on the catchment area and the network analysis, the study analyzes data on land use, population density, accessibility, and surrounding variables to determine catchment areas to analyze neighborhood park accessibility. The study results show that the selected case study, the Bader District, which is one of Amman's most densely populated areas, experienced an erroneous distribution of neighborhood parks due to a lack of established planning regulations, resulting in a shortage of the percentage of the district's open spaces and parks dedicated to the population comparable to international standards. The research emphasizes GIS's potential as a significant tool for urban planning and community development, as well as insights into how parks might be strategically positioned to improve a neighborhood's livability by identifying areas in the neighborhood underserved by current parks and prospective locations for additional parks. Consequently, criteria are proposed and applied to the case study, and new locations for any suggested future parks are selected based on catchment areas. It should be noted that the results of this research may apply to different categories of parks in various Greater Amman Municipality (GAM) locations.

USING GEOGRAPHIC INFORMATION SYSTEMS (GIS) TO LOCATE NEIGHBORHOOD PARKS BASED ON THEIR CATCHMENT AREA

Keywords: *Geographical Information system (GIS), Neighbourhood Park, Catchment Area, Accessibility, Bader District.*

ملخص. تعاني مدينة عمان من نقص في المساحات المفتوحة والحدائق العامة في الأحياء السكنية والتي يعتبر وجودها عنصرا أساسيا لتحسين نوعية الحياة في المجتمع وتشجيع ممارسة الرياضة البدنية، وتحفيز التفاعل الاجتماعي. وتلفت هذه المشكلة الانتباه إلى غياب معايير التخطيط في المدينة إلى جانب ضعف الإطار التنظيمي لتوزيع واختيار موقع المساحات المفتوحة والحدائق ومساحاتها التي تتناسب مع عدد سكان المدينة. تركز هذه الدراسة على استخدام نظم المعلومات الجغرافية (GIS) لتحديد نطاق الخدمة للحدائق الحالية في منطقة الدراسة ولاقتراح المواقع الأمثل لحدائق الأحياء السكنية التي تتناسب وحجم المنطقة وعدد السكان، وذلك من خلال تحليل البيانات المتعلقة باستخدامات الأراضي والكثافة السكانية والمتغيرات المحيطة لتحديد نطاق تأثير كل حديقة باستخدام أداة تحليل الشبكة الخاصة ب ArcGIS 10.1 وتطبيقها على منطقة الخدمة (catchment area). تظهر النتائج أن الحالة الدراسية المختارة، منطقة بدر، والتي تحتوي على واحدة من أكثر مناطق عمان كثافة سكانية، تشهد توزيعًا غير عادل لحدائق الأحياء السكنية بسبب عدم وجود أنظمة تخطيط متبعة، مما أدى إلى نقص كبير في النسبة المئوية لحدائق المنطقة مقارنة بالمعايير الدولية. كما يؤكد البحث على إمكانات نظم المعلومات الجغرافية كأداة مهمة للتخطيط الحضري وتنمية المجتمع من خلال استخدامه في اختيار أماكن مقترحة لإنشاء حدائق جديده وذلك بالاعتماد على نطاق تأثير وخدمة كل حديقة للمناطق السكنية المجاورة لها بشكل استراتيجي لتحسين نوعية الحياة في الحي السكني. ومن الجدير بالذكر أن هذه الدراسة يمكن تبنيها وتطبيقها على مختلف أنواع الحدائق أو الخدمات في مختلف مناطق أمانة عمان الكبرى.

الكلمات المفتاحية: *نظم المعلومات الجغرافية، حدائق المجاورة السكنية، نطاق الخدمة، إمكانية الوصول، منطقة بدر.*

1. Introduction

Open areas serve as more than just relaxation spots. They encourage spontaneous social connections that can benefit both physical and psychological health, enhance communities, and make cities and neighborhoods more attractive places to live. Well-designed and easily accessible public open spaces encourage outdoor activities like walking and cycling, bringing people together and fostering frequent engagement (Pasaogullari and Doratl, 2004; Humpel et al., 2002). Public parks are particularly crucial elements of urban planning, contributing to the social, economic, ecological, and aesthetic aspects of the urban fabric (Rubaszek et al., 2023). Unfortunately, in densely populated areas like Amman, many neighborhoods lack public open spaces and rely instead on streets and worship places for social interaction.

Governmental agencies are responsible for developing standards and criteria for the distribution of parks within the city. However, the Greater Amman Municipality currently lacks planning standards for determining ideal park locations, resulting in a scarcity of parks and public spaces throughout the city's residential areas. Although a specialized department within the Greater Amman Municipality administers the parks and open spaces in the city of Amman, there are no park guidelines or neighborhood planning recommendations for park placement, size, population served, or service area (Al Hiary, 2004). Inadequate planning standards and laws that neglect existing parks have a significant impact on the quality of these parks. Tewfik & Amr (2014) assert that Jordan's land use policy, especially in Amman City, lacks appropriate land use planning due to inconsistent laws. Typically, park sites are selected after sorting through other neighborhoods' land uses. The selection of park plots receives no special consideration and is usually chosen after determining all other lands; in most cases, they are leftover plots.

Amman City contains 143 parks distributed over twenty-two districts with approximately 230 neighborhoods and villages of varying sizes, populations, and park availability (GAM, 2023). As shown in Figure 1, the locations of public parks are random since some zones have many parks and open spaces, such as Al Madinah District, which has an area of 229 m2 of public open spaces. Conversely, other zones have no such spaces, like Uhod District, proving that the distribution of parks is not subject to criteria or standards.

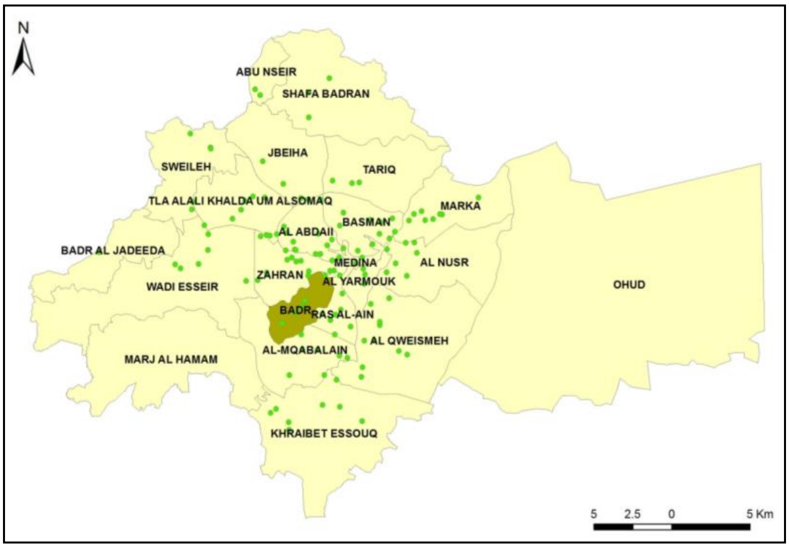


Figure 1. The Distribution of Parks in Amman's Districts.

City Deputy Director for Health and Agricultural Affairs, Mervat Muhairat, stated that GAM seeks to establish 13 parks and gardens, in addition to maintaining and repairing 26 other parks and gardens, as part of the plan to increase the per capita share of green spaces to 2.5 percent instead of 1.6 percent in its new strategy, "Amman Green City Action Plan" (The Jordan Times, 2022). However, choosing places for parks remains a challenge as it determines how often locals will utilize them and whether they will serve their intended purpose.

Sixty percent of Amman's parks have areas of less than 20,000 square meters, making them pocket and neighborhood parks by international standards and classifications of parks and open spaces. The study aims to locate neighborhood parks using contemporary GIS technology based on the catchment area that the park serves.

2. Literature Review

2.1 ACCESSIBILITY STANDARDS IN OPEN SPACES AND PARKS

Parks are essential for residents of neighborhoods to enjoy and benefit from, and their accessibility plays a critical role in their utilization. Criteria such as distance thresholds and physical impediments must be considered to measure accessibility accurately (CABE Space, 2009; Nourian et al., 2015). Park planners assess accessibility using indicators such as distance, proximity, park area per capita, and number of parks to determine their spread in the city and provision to residents (Oh and Jeong, 2007; Kwan & Weber, 2003; Handy & Niemeier, 1997). Many studies have analyzed spatial equity in parks using accessibility measures, and accessibility standards are crucial to ensuring that open spaces and parks continue to serve their intended purpose. (Rubaszek et al., 2023; West Devon Borough Council, 2017; CABE Space, 2009).

Several studies on walking distance have employed different technologies and methods to assess accessibility in urban areas. Zhang and Wang (2006) conducted a study using landscape metrics to calculate the spatial configuration of green spaces and provided network analyses based on GIS to analyze the factors that positively affect the accessibility of proposed green spaces. Nourian and colleagues (2015) proposed many accessibility measures based on an 'EasiestPath' algorithm that also provides the true temporal distance between sites. This algorithm searches for paths that are as short, flat, and straightforward as possible, using fuzzy logic to generate catchment zones and enable mapping 'closeness' while considering preferences, such as 'how far' someone is willing to walk or cycle to reach a

given destination. The accessibility criteria are integrated into the CONFIGURBANIST toolbox, which allows for real-time analysis of urban networks for design and planning.
Lima and others (2022) implemented a grammar-based multi-objective approach to tackle trade-offs in the generation of urban fabrics in early design. The approach was illustrated by implementing specific grammar that codifies the guidelines for designing the Chicago urban fabric to generate integrated and walkable areas while consuming fewer resources and potentially emitting less CO_2.

Accessibility is related to the area served by the open space (service area), which is otherwise called a catchment area, defined as the geographical area that is populated by visitors for the specific facility (Andersen & Landex, 2009) therefore, catchment area analysis depends on the demand population being connected to accessibility (Bozdo et al., 2013).

2.2 CATCHMENT AREA BASED ON GEOGRAPHICAL INFORMATION SYSTEM

The catchment area is a crucial parameter used to measure accessibility and determine the extent of the influence of open spaces and parks on neighborhoods. It measures accessibility and has various applications, including planning the distribution of public open spaces (Navalkar, 2014; Open Space Planning and Design Guide, 2013). The term catchment area originated in 1951 in London, when the standard of "acres per thousand populations" failed to assess existing open spaces' effectiveness and accessibility (Turner, 1992). Its definition varies depending on context but refers to the "sphere of influence" of open spaces in terms of travel, use, and its role within the open space system. Catchment can be explained using distance, travel time, the site's role, scale, quality, level of services, and maintenance (Open Space Planning and Design Guide, 2013).

Turner (1992) stated that a study conducted in 1964 showed that there is a relationship between the catchment area parameter and the park's size as we can see in Table 1.

TABLE 1. Relationship between Parks’ Size and their Catchment Area.

Parks Size	Catchment Area
8000 m^2 to 198000 m2	Up to 400 m
200000 m^2 to 600000 m2	1200 m
over 600000 m^2	3200 m to 8000 m

Determining the geographical catchment area involves defining its geographical boundaries through buffer analysis and the distance that defines the size of the buffer can be determined through willingness to walk criteria. Since the catchment is also a measurable quantity and has geometric attributes, GIS technology can be used as a representational tool to represent the complexities in the catchment (Navalkar, 2014).

The innovation of GIS gave great momentum to the shift in the urban planning paradigm from a model based to a computer-based approach (Batty, 1994). GIS brings together different types of data for intelligent planning and helps with green space project management and site selection in urban areas, improving insight for decision-making (Tasoulasa et al. 2013).

There are three main approaches for representing catchment areas when planning open spaces: the circular buffer approach, the service area approach, and the time resistance approach (Andersen & Landex, 2009). To determine the distribution of open spaces, various data are needed, including location, accessibility, open space-to-population ratio, and other relevant data. Using GIS to represent the catchment area of the open space can help identify served and non-served areas and integrate diverse data with geographic location, making it a useful decision-support tool for planning open spaces.

The study adopted the service area approach using GIS-based catchment area analyses. The Service Area Approach is the most realistic approach for catchment area analysis since it is based on actual routes to certain places and is suitable for examining accessibility improvements to open spaces. Time can be added as a resistance element in network research to refine the approach even further. Researchers, policymakers, and urban planners have used GIS in conjunction with multiple criteria decision systems to choose suitable sites for green spaces, which is a crucial factor when building open spaces and parks (Ziari et al., 2013).

GIS is a helpful tool for managing and selecting open space projects and reducing management costs. By integrating different map layers into an open space site selection project, GIS proves to be helpful for intelligent planning since it gives insight to decision-makers working in the process (Tasoulasa et al., 2013). Several researchers have studied the distribution of open spaces using GIS software. Laghai and Bahmanpour (2012) evaluated the green spaces of Tehran using GIS software and map overlaying and found that the green spaces were distributed improperly and had low social and ecological efficiency.

Aultman-Hall et al. (1997) calculated neighborhood pedestrian accessibility by measuring the distance between homes and destinations (e.g., school, transit, parks) and digitizing the neighborhood layout into

ArcInfo GIS software. Javed et al. (2013) focused on the spatial distribution of existing neighborhood parks based on road network accessibility, using the time resistance approach to calculate the time required to walk from residences to parks. It has used GIS network analysis based on connected road network data to calculate the different time zones with a standard walk time impedance of 60 meters per minute. This study aims to establish neighborhood park accessibility zones based on walk time impedance and assess existing neighborhood park accessibility concerning calculated served areas and population.

Tudor Morar et al. (2014) used GIS to assess pedestrian accessibility to green space by comparing the green space per capita parameter to the accessibility to green space per capita required by Romanian legislation. Mohammadi and Parhizgar (2009) analyzed the spatial distribution and location of urban parks in District No. 2 of Zahedan City using GIS and found that there were not enough neighborhood parks in the studied region. Schlossberg and Brown (2004) determined pedestrian catchment areas and intersection densities using GIS. Pedestrian catchment areas (PCA), also called ped sheds, define the area around some point that one could access via a path network using a fixed distance. A sixty percent ratio is considered a “good” walkable environment. Schlossberg and Brown (2004) computed pedestrian catchment areas for each TOD using an ArcView GIS extension called Network Analyst, resulting in an impeded pedestrian catchment area (IPCA) that indicates the degree to which hostile or large streets impact the likely walkable area around a fixed location.

2.3 BADER DISTRICT

There is a significant variation between the several Amman districts in terms of the percentage of total park area to district area. Bader District was chosen as a case study because its park ratio of 0.4% is in the middle of the ratios, putting it between the other districts where parks make up between 0.1% and 0.8% of the total district area.

In addition to its convenient location, Bader District was chosen because it contains the Al Akhdar neighborhood, one of the city's most densely inhabited areas (The Department of Statistics, 2014). Despite its high population density, Al Akhdar only has a single park for its roughly 80,000 residents. Al Thra'a Neighbourhood is another densely populated neighborhood in the district and lacks green spaces or parks. The Dahyet Al Yasmeen neighborhood is a freshly organized area and is fast expanding, with many new housing buildings that are served by one park (GAM, 2023).

The Bader District can be found in the southern part of Amman City. It covers an area of 9.878 km^2 and is located at 3534000–3538000N latitude and 772000–776000E longitude GAM (2023). According to a 2015 report from The Department of Statistics, the population of the district is estimated to be around 229.000 people (city population, 2023). Figure 2. shows that the Bader District is composed of five neighborhoods: Al Akhdar Neighborhood, Al Helal Neighborhood, Al Thira'a Neighborhood, Al Homranyeh Neighborhood, and Al Yasmeen Neighborhood. These neighborhoods vary in size and population (GAM, 2023).

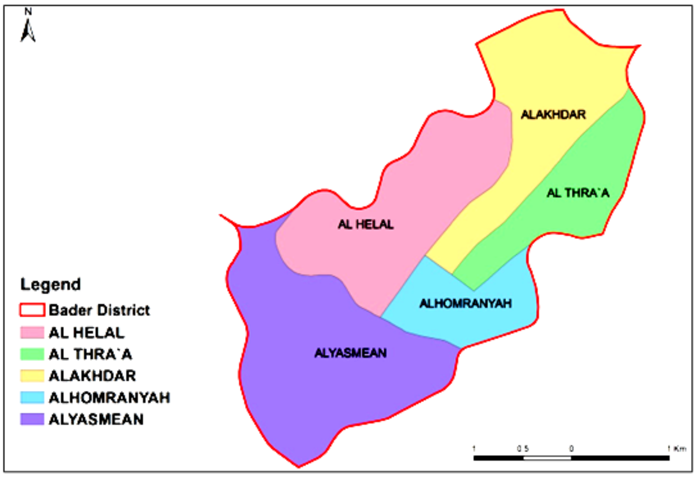


Figure 2. The Neighborhoods of Bader District.

In the Bader district, Table 2. depicts the state of the surrounding neighborhoods. Two of the neighborhoods lack any available open spaces or parks, while the others have one or a maximum of two parks. Additionally, the allocated park areas within the neighborhoods fall short of the required amount.

TABLE 2. Neighborhoods of Bader District

Neighborhood	Population	Area (m^2)	Density	Park Names	Park sizes (m^2)	park-to-area ratio
Al Akhdar	79862	2085612	0.038	Al Shoura	15616	0.7%
Al Thra'a	50502	1308195	0.039	_	0	0.00%
Al Yasmeen	14754	106764	0.005	AlYasmeen	10133	0.3%
Al Helal	34066	2388494	0.014	Kafr Raee Al Shabab	8200 9200	0.7%
Al Homranyh	1998	996663	0.002	_	0	0.00%

Four parks are categorized and permitted by The Department of Studies and Design in GAM as Public Park in Bader District. Three of them are located close to each other in the middle of Bader District. As for the areas of the parks, they range between 8200 m^2 for the smallest one and 16000 m^2 for the largest one. They are distributed in three different neighborhoods with a total area of approximately 43,149 m^2, which is 0.4% of Bader District's total area. (See Figure 3.)

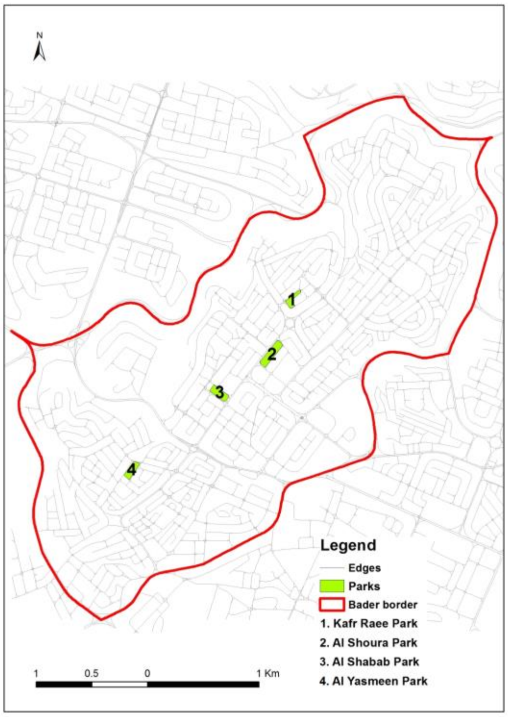


Figure 3. Spatial Distribution of Parks in Bader District.

3. Methodology

A mixed-methods approach was used to undertake this study, as follows:
First, a theoretical framework is founded on a literature review to provide an understanding of the theories and techniques utilized in site selection processes like the Geographical Information System (GIS) and its applications in the catchment area and network analysis. Collecting data from specified documents about neighborhood parks, examples of guidelines, and criteria for distributing parks in various countries to provide a well-informed decision regarding location selection.

Next, an analytical approach was taken by analyzing a local district, Bader District, as a case study. This involved identifying the distribution of open spaces and problems in the area. Data was gathered from various institutions, including the Department of Parks, the Department of GIS, the Department of Statistics, and other concerned institutions. The data gathered is utilized to estimate the catchment areas of existing parks, employing ArcGIS 10.1's Network Analyst software. Additionally, The Spatial Analyst software is used to determine optimal locations for new parks based on established criteria and catchment area analysis.
This approach allowed for a comprehensive analysis of the area and provided valuable insights for making informed decisions regarding park locations.

4. Data Analysis and Results

An assessment of the locations of existing parks in the Bader District was conducted. Datasets were gathered and prepared using various sources; datasets were prepared by using ArcGIS 10.1 software to complete the analysis.

The Data of open spaces of Amman’s City District was collected from The Department of Studies and Design in GAM and population data for the same area was collected from the Department of Statistics for the year 2015.
Geographic Information System software ArcGIS 10.1 was used to produce different maps for analysis. The first layer, which was used as the base map is the latest satellite image. Applications and Planning Survey which was used for Bader district in ArcGIS 10.1. The second layer was the land use from GAM as a CAD file that was converted to Shapefile and then to Geodatabase to be used in ArcGIS 10.1 as a reference of the land use and overlaid by different layers. The third layer was the buildings redrawn as polygons from the GAM maps. The fourth layer was the roads represented in the form of lines as the network of travel. The fifth layer was the points for the locations of different parks maintained by the Municipality to understand the spatial distribution of these parks in the Bader district. And there is a layer produced for the future residential buildings as points on the unconstructed residential lands to estimate the future total population.

The most used method to evaluate the catchment area for parks is to create a service area representing a walking distance and to examine the population within that service area (Handy & Niemeier, 1997).

For assessing parks’ accessibility, the criteria from international standards were used. It concluded that the neighborhood parks ranging between

$4000m^2$ to $20000m^2$ serve a catchment area of 400 m with a level of service of 2000-5000m2 per 1000 population.
The road data was transformed into pedestrian network ways by using the ArcGIS network analyst tool. Studies show that walking speed ranges from 4.5 km/h to 5 km/h, so, the average walking speed is 4.8 km/h (Chartered Institution of Highways and Transportation, 2023; Morar et al., 2014).
4.8 km/h = 80 m/ minute, which means that the above-mentioned distance (400m) takes 5 minutes to reach the park. It is to be noted that the nature of streets in Amman is steep and not easy to walk through, and the conditions of the sidewalks are not encouraging to walk, so the time calculation could be not accurate. Therefore, distance has been adopted in the calculation.

Buildings representing residences were digitized on each residential land and their height has been taken into consideration when calculating the number of floors that each building consists of. The population was then distributed into each residence according to the calculation that every floor has two apartments with 4.8 persons for each apartment (The Department of Statistics, 2015). The equation used to estimate the population is,

Number of floors x 2 apartments x 4.8 people.

For estimating the future population, the number of residential lands that have not been constructed yet had been calculated. According to buildings law, residential land consists of a maximum of four floors for each residential building, and the average contains two apartments on each floor.
The estimation of future population = Num. of future buildings x 4 floors x 2 apartments x 4.8 people.

As a result, the estimation of the existing residential population and the number of future residents gives a total population for the study area.

A Catchment area was derived for each park from its entry point using the road network by ArcGIS 10.1’s Network Analyst Tool. The service areas for each park were merged so that each service area represents access to a park as shown in Figure 4.

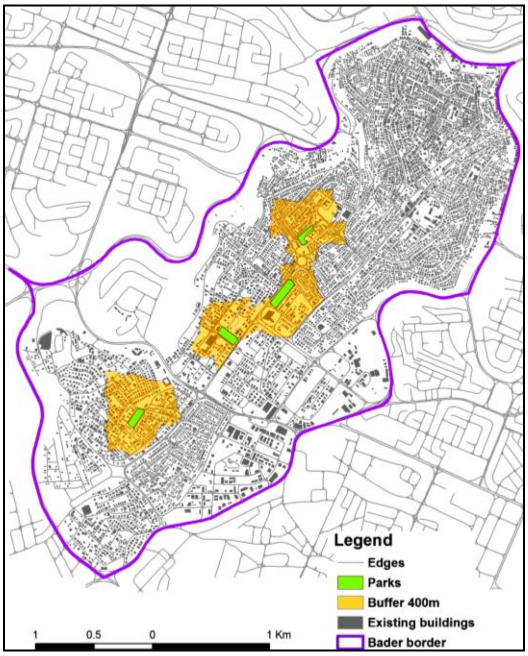


Figure 4. Catchment Areas of The Existing Parks in Bader District.

As a result, the total catchment area for all the existing parks is approximately 13% of Bader District which covers 45047 residents of Bader District, which means there are 87% of Bader District residents out of the catchment areas of all existing parks.

The parks located on main streets like A-Shura and A-Shabab parks have less catchment area than the parks located in the middle of residential buildings because the main streets make a border and prevent the access of pedestrian residents. On the other hand, parks surrounded by secondary streets between residential blocks are more accessible for pedestrian users and cover more buildings with their catchment areas Figure 5.

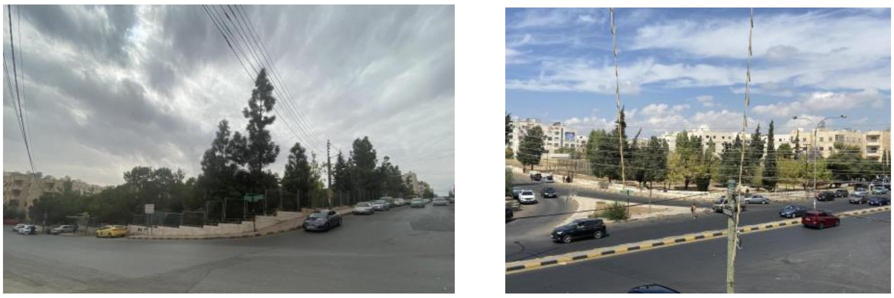


Figure 5. Al Yasmeen Park (Left). Al Shabab Park (Right)

4.1 PROPOSED ALLOCATION FOR NEW PARKS

This research employs spatial analysis in ArcGIS 10.1 to make more informed decisions about the best locations for new parks by examining the locations, attributes, and relationships of features in spatial data through overlaying and other analytical techniques.

The procedure was carried out in four steps by the GIS spatial analyst tool, which are:

Firstly, the land use layer was used to identify vacant lands in the area of interest. A total of 2535 lands were found. However, to prevent overlap among catchment areas, the second condition includes all lands excluding those that intersect with extant parks and their service area; therefore, 2078 lands are available for selection, as shown in Figure 6.

The next step was to locate locations for neighborhood parks with sizes between 4,000 and 20,000 square meters. Because most of the land in the region is residential property with limited areas, some of the neighboring lands have been incorporated. As depicted in Figure 7, the results indicated that 64 parcels of land in Bader District met the selection criteria.

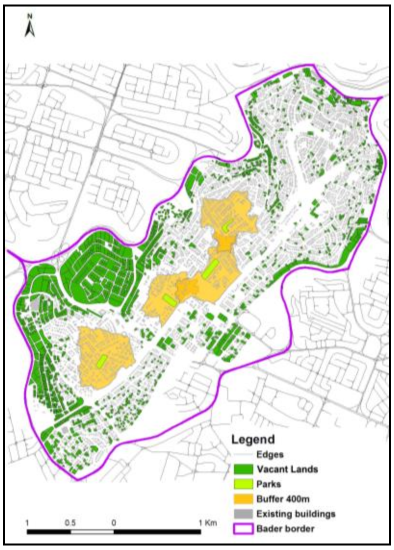


Figure 6. Vacant Lands in Bader District.

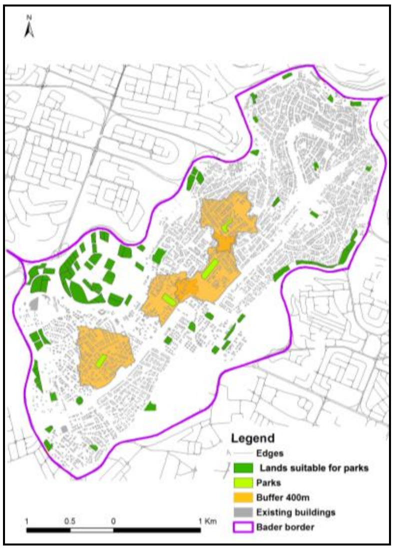
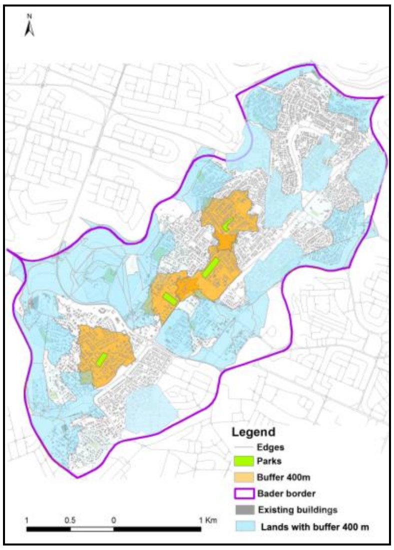


Figure 7. Vacant Lands less than 20000 m2.

Figure 8 illustrates the catchment areas of the 64 lands at a distance of 400 meters, which helped to identify the service areas that particular lands could serve and to determine the best places for parks. Finally, when deciding where in Bader District to put parks, it's important to find spots that are convenient for as many people as possible while also giving as much coverage as possible in the area of interest, as we can see in Figure 9.



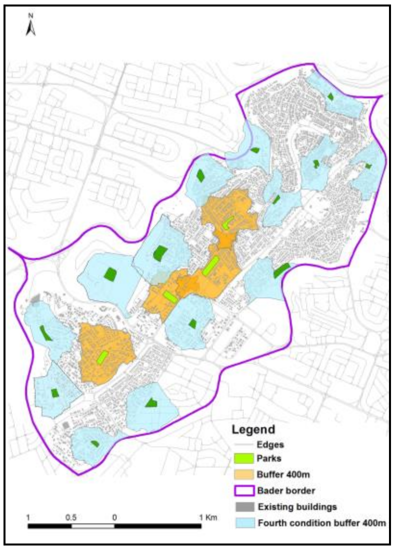


Figure 8. The catchment areas for the selected lands. *Figure 9*. The Optimal locations of parks In Bader district and its Catchment Areas.

According to the recommended allocation, 16 of the chosen distributed sites met all the requirements for use as neighborhood parks. Although it is not yet complete, it could play a role in a wider process that aims to give urban specialists and planning decisions a solution, making it possible to realize Amman's goal through systematic and effective planning.

5. Conclusion

This study utilized GIS Network Analyst software and census data to analyze the size and spatial location of parks in Bader District. The goal was to determine the extent of parks' influence on neighborhoods and assess access to neighborhood parks according to international standards to assist in the selection of new sites for neighborhood parks. The results showed that only 13% of Bader District's population resides within 400 meters of neighborhood parks, indicating an uneven allocation of parks. The study also found that parks located on main streets have a limited catchment area due to the street acting as a barrier to visitors. i.e., A-Shura and A-Shabab parks.
The results shed light on the lack of planning and distribution studies for parks in Amman's neighborhoods. The findings can inform ongoing

discussions and research related to local planning processes and demonstrate how GIS and spatial analyses can quantify the accessibility of community services. The study highlights the absence of open spaces and parks in Amman's neighborhoods, which play a significant role in social community life.

Considering the study's findings, a set of suggestions has been made to guide city planners in making strategic decisions about allocating new parks throughout the city.

1. City planners should avoid placing parks next to major thoroughfares to reduce the threat of vehicles.
2. The neighborhood's pedestrian infrastructure must provide easy access to all other areas. Paths in public spaces should be well-maintained and easy to use for all users.
3. Parks should be accessible and visible within a distance of 400–500 meters since most park visitors care most about how close, secure, and centrally located a park is
4. Raising public awareness of the benefits of walking and sitting outside for physical and psychological health for both children and adults
5. Finally, the study recommends expanding the use of GIS to organize all other services provided to city users, leading to better functional city development.

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EVALUATING SPATIAL JUSTICE THROUGH THE ANALYSIS OF THE RELATIONSHIP BETWEEN HOUSE PRICES AND THE ACCESSIBILITY TO URBAN INFRASTRUCTURES WITH A BIG DATA APPROACH

A Comparative Case Study of Beijing and Shanghai in China

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Abstract. The rapid development of cities has caused many problems of spatial injustice in urban communities. However, how to detect and measure such injustice has not been fully developed yet. With open-source urban big data and advanced data analysis methods, this study evaluates spatial justice in cities by analyzing the relationship between the house prices of communities and the accessibility to urban facilities. It investigates the accessibility to critical infrastructures mainly in five dimensions: public transportation, shopping, education, health care and recreation. The whole research is grounded by a comparative case study of the two biggest cities in China, Beijing and Shanghai. Integrating the big data of 5394 communities from these two cities, this study examines if the house prices of communities are highly related to the convenience of accessibility to urban infrastructures, which can inform if there is any spatial injustice in Chinese cities. Findings indicate that the situations of spatial justice in Beijing and Shanghai are pretty different. Residents in Beijing City have relevantly equal access to urban facilities, which has little connection with house prices, while citizens in Shanghai may experience a spatial injustice as people living in higher house-price communities have noticeably better accessibility to urban amenities. Such a distinct difference may come from the different urban planning policies in these two cities, as the former has a human-centred equality-minded approach to embody the political significance while the latter takes rapid economic development as its priority for urban planning.

Keywords: *Spatial justice, house price, accessibility, urban infrastructures, big data.*

ملخص. لقد تسبب التطور السريع للمدن في العديد من مشاكل الظلم المكاني في المجتمعات الحضرية. ومع ذلك، فإن كيفية اكتشاف وقياس هذا الظلم لم يتم تطويرها بالكامل بعد. باستخدام البيانات الضخمة الحضرية مفتوحة المصدر وطرق تحليل البيانات المتقدمة، تقوم هذه الدراسة بتقييم العدالة المكانية في المدن من خلال تحليل العلاقة بين أسعار المنازل في المجتمعات وإمكانية الوصول إلى المرافق الحضرية. ويدرس إمكانية الوصول إلى البنى التحتية الحيوية بشكل رئيسي في خمسة أبعاد: النقل العام والتسوق والتعليم والرعاية الصحية والترفيه. يرتكز البحث بأكمله على دراسة حالة مقارنة لأكبر مدينتين في الصين، بكين وشانغهاي. من خلال دمج البيانات الكبيرة لـ 5394 مجتمعًا من هاتين المدينتين، تدرس هذه الدراسة ما إذا كانت أسعار المنازل في المجتمعات مرتبطة بشكل كبير بسهولة الوصول إلى البنية التحتية الحضرية، والتي يمكن أن تبلغ ما إذا كان هناك أي ظلم مكاني في المدن الصينية. تشير النتائج إلى أن أوضاع العدالة المكانية في بكين وشانغهاي مختلفة تمامًا. ويتمتع المقيمون في مدينة بكين بإمكانية الوصول على قدم المساواة إلى المرافق الحضرية، والتي لا علاقة لها بأسعار المساكن إلا قليلاً، في حين قد يواجه المواطنون في شنغهاي ظلماً مكانياً لأن الأشخاص الذين يعيشون في مجتمعات ذات أسعار مساكن أعلى يتمتعون بإمكانية وصول أفضل إلى المرافق الحضرية بشكل ملحوظ. قد يأتي مثل هذا الاختلاف الواضح من اختلاف سياسات التخطيط الحضري في هاتين المدينتين، حيث أن الأولى لديها نهج يركز على الإنسان ويركز على المساواة لتجسيد الأهمية السياسية في حين أن الأخيرة تأخذ التنمية الاقتصادية السريعة كأولوية لها في التخطيط الحضري.

الكلمات المفتاحية: *العدالة الفراغية، تكلفة المسكن، إمكانية الوصول، البنية التحتية الحضرية، البيانات الضخمة.*

1. Introduction

In the rapid development of cities, the problem of spatial justice has gradually become an essential concern for many urban researchers worldwide, as the planning of urban resources such as essential infrastructures has a significant effect on people's everyday life practices (Fainstein, 2009; Soja, 2010; Bhide, 2015; Weck et al., 2022). As clearly stated by the United Nations (2015) in the Sustainable Development Goals (SDGs), urban spatial justice is essential to achieve the 10th SDG of "Reduced Inequalities" (United Nations, 2015). Under the background that "income inequality is on the rise - the richest 10 percent have up to 40 percent of global income whereas the poorest 10 percent earn only between 2 to 7 percent" (United Nations, 2015), the gap between

the poor and wealthy people has gradually become more and more significant in recent years (Heiserman and Simpson, 2017). However, a city is a common place, and everyone should have an equal right to live in it and access essential urban infrastructures (Lefebvre, 1968; Soja, 2009). The re-examination and re-insurance of such urban spatial justice become even more crucial nowadays, especially in the circumstance that the worldwide economic recession induced by the global outbreak of the Covid-19 pandemic has further aggravated the gap between the rich and the poor during the past three years (Abbasi-Shavazi, 2021; Taylan et al., 2022).
In contemporary cities, the problem of spatial injustice mainly happens when various groups of citizens with different gender, age, ethnicity, income and other features experience a significant difference regarding their accessibility to essential urban infrastructures (Fainstein, 2009; Soja, 2010). In China, as the government has a long-term adherence to the ethnic unity policy (Hinton, 2011), people of different races have the same rights to access public resources (Shutao, 2009). Moreover, ethnic minorities even have the privilege over the primary ethnicity to access some urban resources, such as schools and colleges (Shanxin, 2009). The implementation of these policies ensures that different ethnic groups can have equal access to urban infrastructures. However, as a developing country that has been implementing economic growth as its basic national policy for the last twenty years (Zhang, 2022), China is experiencing an increasingly big gap between the rich and the poor (Zuo and Hong, 2022). Whether people with different income levels are experiencing spatial injustice regarding their accessibility to urban infrastructures in cities may need a closer examination. With open-source urban datasets, this research investigates the relationship between the house prices of communities and their accessibility to various facilities to detect if there is any spatial injustice in Chinese cities.

2. Literature Review

2.1. THE CONCEPT OF SPATIAL JUSTICE

Originally, the concept of spatial justice was derived from the notion of "the right to the city" in Lefebvre's (1968) book: *Le Droit à la ville [The right to the city]*. He proposed that the right to the city is indeed the "right to urban life" (Lefebvre, 1968, p. 64), manifesting itself as "a superior form of rights: right to freedom, to individualization in socialization, to habitat and to inhabit" (Lefebvre, 1968, p. 73). Subsequently, the notion of "the right to the city" was developed by Harvey (1973) in his book *Social Justice and the City,* where he highlighted the close relationship between socio-spatial justice and citizens' accessibility and proximity to urban resources (Harvey, 1973, p. 69). Recently, the notion and theory of spatial justice were officially proposed by Soja (2009, 2010) in his book, *Seeking Spatial Justice*, and the definition of spatial justice is explained as “the fair and equitable distribution in space of socially valued resources and the opportunities to use them” (Soja, 2009, p. 2). Nowadays, much research has indicated that the distribution of urban resources closely connects with urban spatial justice (Soja, 2009; Fainstein, 2009; Hilmers et al., 2012; Setianto and Gamal, 2021; Weck et al., 2022).

2.2. RELATED WORK ON THE RESEARCH TOPIC

Although plenty of studies have discussed the topic of urban spatial justice for the last decades, most of them concentrated on Western cities or examined the problem of spatial injustice qualitatively by interpreting the urban planning policies regarding the distribution of urban resources. For example, Fainstein (2009) investigated the relations between spatial justice and urban planning, proposed a planning approach for creating a just city, evaluating the planning practices and urban spatial justice in three cities of New York, London and Amsterdam. Hafeznia and Ghaderi (2015) proposed a way to conceptualize spatial justice from a political geography perspective, while Shucksmith et al. (2020) proposed a political development policy approach to achieve spatial justice both distributively and procedurally through a case study of England.
For the research of urban facilities and spatial justice, Amer (2007) proposed a spatial-analytic GIS-based approach to address the urban health facilities planning for spatial justice, and Asefi and Nosrati (2020) examined the spatial justice in the distribution of built outdoor sports facilities. In addition, Jian et al. (2020) investigated spatial justice in public open space planning from the perspectives of accessibility and inclusivity; Yazar and York (2023) explored nature-based solutions through collective actions for spatial justice in urban green commons, and Mahmoudi et al. (2019) evaluated the spatial justice in people’s accessibility of urban public parks in Tehran city of Iran.
For the studies of house prices and the accessibility to urban facilities in China, some research has examined these two aspects separately, but their relations have not been investigated systematically and quantitatively yet. For example, Hsu et al. (2022) examined the housing prices in Beijing and revealed that inner facilities like yards and sports field have magnificent impacts on house price, illustrating that house price has a strong correlation with micro public space quality. Li et al. (2021) found that there is a close relationship between house prices and urban vitality, which is a key indicator for measuring urban development. In addition, Yin et al. (2019) examined the spatial justice of a Chinese metropolis through the analysis of housing price and income ratios in Nanjing, China. However, these studies on house prices did not examine the relationship between house prices and accessibility to urban facilities, while

the research on accessibility has not yet been combined with house prices in Chinese cities. For instance, Zeng et al. (2017) studied the spatial pattern of the accessibility to community service facilities of low-income communities in Nanjing, China, while Hussaini et al. (2023) inspected the spatial justice in relation to the urban amenities distribution in Austin city of the United States through the analysis of the GIS data and the Fuzzy logic model.

Currently, how to quantitatively evaluate spatial justice for vulnerable groups in urban communities regarding their accessibility to infrastructures is still a gap that needs more attention. Moreover, few studies have examined spatial justice in Chinese cities by analyzing the accessibility of urban communities to nearby facilities, especially for low-income residents. This study may fill this research gap by using big data techniques to quantitatively evaluate spatial justice in Chinese cities by analyzing the relationship between the house prices of urban communities and their accessibility to critical infrastructures.

3. Datasets and Methodology

3.1. DATASETS INFORMATION

This study is grounded by a comparative case study of Beijing and Shanghai in China. The dataset of Beijing City is obtained from the Bejing City Lab[1] of Tsinghua University, and it includes 1167 communities in the central urban areas of Beijing within the Second Ring Road. The dataset of Shanghai City is obtained from the Shanghai Public Data Open Platform[2], a government institution managing the open-source digital data of Shanghai. This dataset covers 4227 communities in central Shanghai within the Inner Ring Road.

Datasets of each city contain two kinds of information: 1) the house prices of communities in central urban areas, which can reflect residents' income levels; 2) the distribution of urban facilities in various dimensions.

The detailed information of the datasets is shown in Table 1.

[1] https://www.beijingcitylab.com/data-released-1/data21-40/

[2] https://data.sh.gov.cn/

TABLE 1. The detailed information of the datasets of Beijing and Shanghai city.

Data Information	Beijing	Shanghai
Research Area	Central Urban area (within the 2nd Ring Road)	Central Urban area (within the Inner Ring Road)
Housing Price	1167 Communities	4227 Communities
Public Transportation Facilities	Bus Stations, Subway Stations	
Critical Shopping Facilities	Shopping Malls, Convenience Stores	
Educational Facilities	Kindergartens, Elementary Schools, Middle Schools	
Health-care Facilities	Hospitals, Community Health Centers, Elder-caring Nursing Homes	
Recreational Facilities	Sports Facilities, Cultural Centers; Cinemas	

3.2. METHODOLOGY

The research methods mainly include three parts: analysis of the house prices, analysis of the accessibility to facilities for each community, and correlation analysis between house prices and the accessibility to infrastructures.
Taking the analysis of Beijing City as an example, the procedures include:
1) Firstly, this research calculates the quartile values of house prices by sorting the prices from the lowest to the highest. With these quartile values, this study divides the housing price levels of Beijing City into four categories:

- low house price: 0 - 25%
- low to medium house price: 25% - 50%
- medium to high house price: 50% - 75%
- high house price: 75% - 100%

2) Secondly, it computes the convenience index of the accessibility to various urban facilities by a series of mathematical calculations for every community. Specifically, it first calculates the raw accessibility by computing the average length of the distances from one community to its nearby facilities within the 15-minute community life circle[3], an area with a radius of 1000 metres from the centre point of the community (Wu et al., 2021). For example, if there are *n* hospitals within the 15-minute community life circle area of a community *x*,

[3] The notion of 15-minute community life circle refers to the concept that residents should meet their urban daily life needs such as shopping, work, entertainment and socialisation within 15 minutes of walking or cycling from their homes (Xiao et al., 2014). It has become a well-recognized concept in the urban planning pratices in China (Yang, 2023).

and the distance of this community to the *i-th* hospital is *d(i)*, then the raw accessibility r_x of this community x to nearby hospital facilities is:

$$r_x = \frac{\sum_{i=1}^{n} d(i)}{\mathrm{n}} \tag{1}$$

Then, with the Min-Max normalization method (Patro and Sahu, 2015), this study scales the averaged distance to a unified range of [0, 1]. As the minimal value of 0 indicates the shortest distance, which means this community has the highest convenience of accessibility to facilities, this research then uses 1 minus the normalized distance to represent the convenience index of the accessibility to surrounding amenities. For example, if R is the set of all the averaged distances r_x calculated with equation (1), then for each community x, its convenience index c_x is:

$$c_x = 1 - \frac{r_x - \min(R)}{\max(R) - \min(R)} \tag{2}$$

Therefore, c_x is the final value to represent the convenience of a community's accessibility to one category of urban facilities, and the larger the value is, the better accessibility to urban amenities the community has.

3) Finally, this research makes a correlation analysis between the house prices of communities and their accessibility indexes to facilities. The results can help this study to investigate if there is any spatial injustice in the city.
The diagram of the research methodology framework is shown in Figure 1.

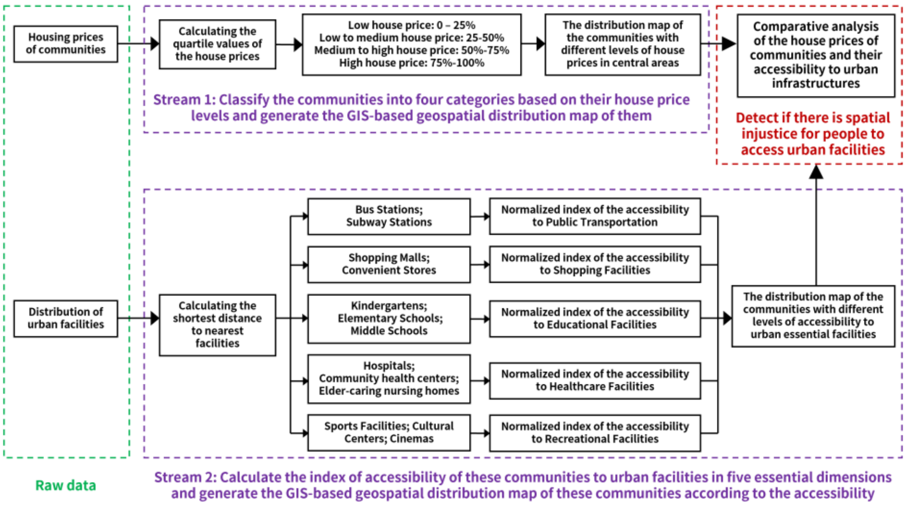

Figure 1. The methodology framework of this research.

4. Case Study and Results

4.1. CASE STUDY OF BEIJING CITY

4.1.1. The housing prices of communities in central Beijing areas

Using the dataset of 1167 communities in central Beijing areas, this research calculates the quartile values of their house prices with the boxplot analysis, and the results are shown in Figure 2. It demonstrates that the lowest price of communities in central Beijing is 9721 Chinese Yuan per square meter while the highest price (not considering the outlier values) is 140000. As shown in Figure 2, the low-house price level is below 58000; low-to-medium is between 58000 and 73000; medium-to-high is between 73000 and 91000; and the high-house price communities are above 91000. The distribution map of these communities based on their housing price levels is shown in Figure 3, where the warmer the colour is, the higher the community's house price is.

Figure 2: Left: The boxplot analysis of the house prices of communities in central Beijing, *Right:* The geospatial map of the communities according to their house price levels.

4.1.2. The accessibilities of central Beijing communities to urban facilities

4.1.2.1. The accessibility to public transportation facilities

The transportation facilities include subway and bus stations. With boxplot analysis, the results of the accessibility to urban facilities for communities with different house price levels are shown in Figure 4. It reveals that the accessibility to subway stations is not correlated with house prices, but the accessibility to bus stations has a relevantly positive correlation with the prices because as the prices increase, the accessibility to bus stations becomes better. However, the improvement is not very large, and communities with different house prices generally have similar accessibility to transportation facilities.

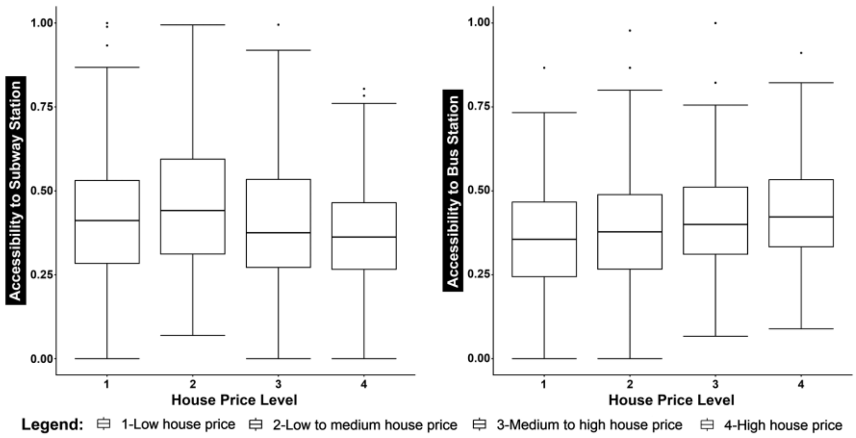

Figure 4. The boxplot analyses of the accessibility to public transportation facilities (subway and bus stations) for central Beijing communities with different house prices.

4.1.2.2. The accessibility to essential shopping facilities

The approachability of essential shopping facilities concentrates on citizens' access to convenient stores and shopping malls, which are critical places for people to obtain their daily life necessities, such as fresh food and groceries.

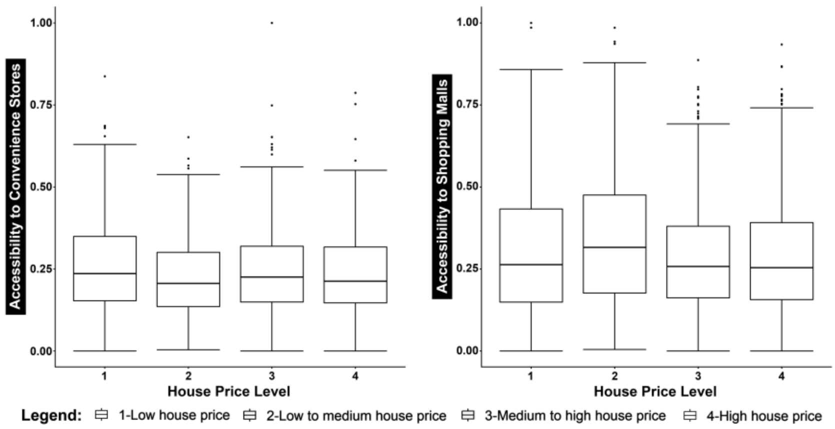

Figure 5. The boxplot analyses of the accessibility to shopping facilities (convenience stores and shopping malls) for central Beijing communities with different house prices.

As shown by the results above in Figure 5, there seems to be no correlational relationship between house prices and the accessibility to shopping facilities, as these communities basically have similar degrees of convenience of access.

4.1.2.3. The accessibility to educational facilities

The educational facilities cover kindergartens, elementary and middle schools, which are vital places for the young to receive education in a city. As shown in Figure 6, the results suggest no inequality in the accessibility to educational facilities, as communities with different house prices have similar access to them, and the lowest house-price communities even have better accessibility than the highest ones to access elementary and middle schools.

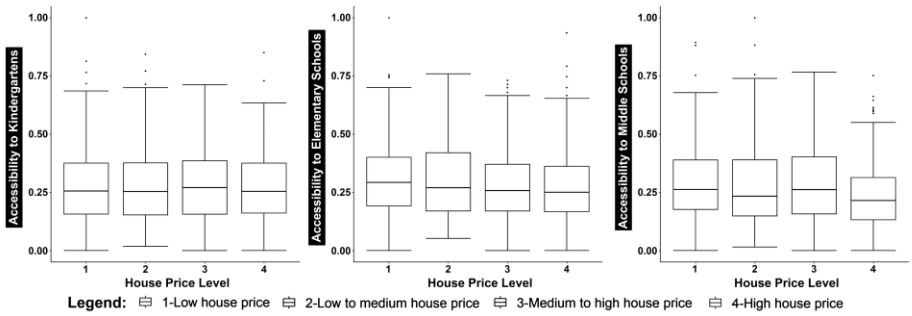

Figure 6. The boxplot analyses of the accessibility to educational facilities (kindergartens, elementary and middle schools) for central Beijing communities with different house prices.

4.1.2.4. The accessibility to health-care facilities

The health-care facilities consist of hospitals, community health centres, and elder-caring nursing homes, which are crucial infrastructures for citizens to receive medical treatments. The analysis results are presented in Figure 7.

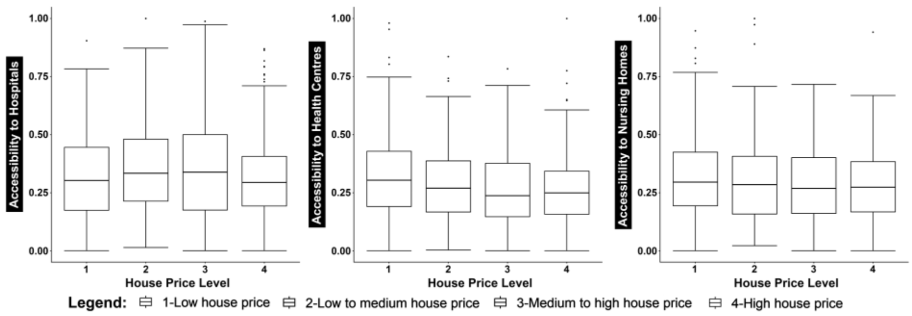

Figure 7. The boxplot analyses of the accessibility to health-care facilities (hospitals, health centres, and nursing homes) for central Beijing communities with different house prices.

It is interesting to find that communities of lower house prices even have better accessibility than higher house-price ones to health centres and nursing homes. Although such correlations are not significant, they at least indicate that there is no spatial injustice for residents with lower income levels to access these facilities. As for the hospitals, whose results are shown in the left graph of Figure 7, the higher house-price communities seem to have better accessibility, but the accessibility index of the highest house-price communities drops and becomes similar to the lowest house-price communities. In summary, citizens living in communities with different house prices have a generally equal and balanced convenience to access health-care facilities.

4.1.2.5. The accessibility to recreational facilities

The recreational infrastructures consist of sports facilities, cultural centres and cinemas, which are indispensable places for people to exercise, attend cultural events and enjoy entertainment. The analysis results are shown in Figure 8.

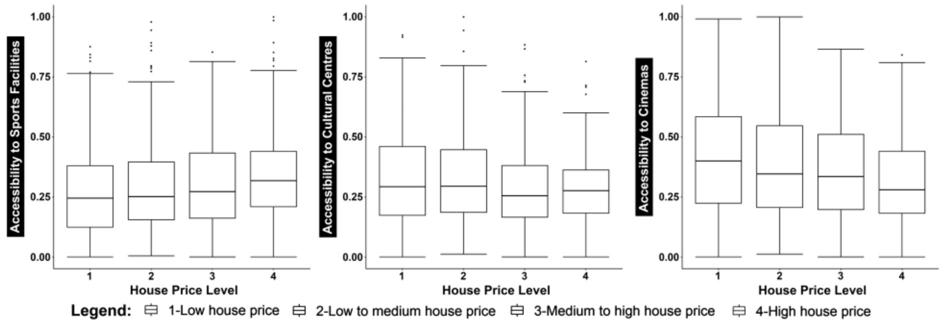

Figure 8. The boxplot analyses of the accessibility to recreational facilities (sports facilities, cultural centres and cinemas) for central Beijing communities with different house prices.

As illustrated in the outcomes above, it is noticeable that as the communities' house prices get higher, they have better accessibility to sporting amenities, while their approachability to cinemas becomes less convenient than the lower house-price communities. These outcomes may indicate that wealthy people are more concerned about their physical health by taking exercise in sports facilities while relevantly lower-income groups may need more entertainment facilities to release their working or life pressures to keep their mental health. Moreover, communities with different house prices basically have relevantly equal accessibility to cultural centres. These results may suggest that people generally have an equitable and balanced approachability to recreational amenities. Although their preferences may differ, citizens of different income levels can usually access such facilities with equivalent convenience.

4.1.3. Correlation analysis between the house prices of central Beijing communities and their accessibility to urban facilities

The results above demonstrate no spatial injustice in the accessibility to urban facilities for communities of different house prices. To further detect if house prices are correlated to the accessibility to urban facilities mathematically, this study uses the raw datasets to examine their statistical relations. With Pearson correlation analysis methods, this study calculates the correlation coefficients between house prices and the accessibility to facilities of the five dimensions above, using the average value of the accessibility within one dimension. The correlation coefficients and the corresponding p-values are shown in Figure 9.

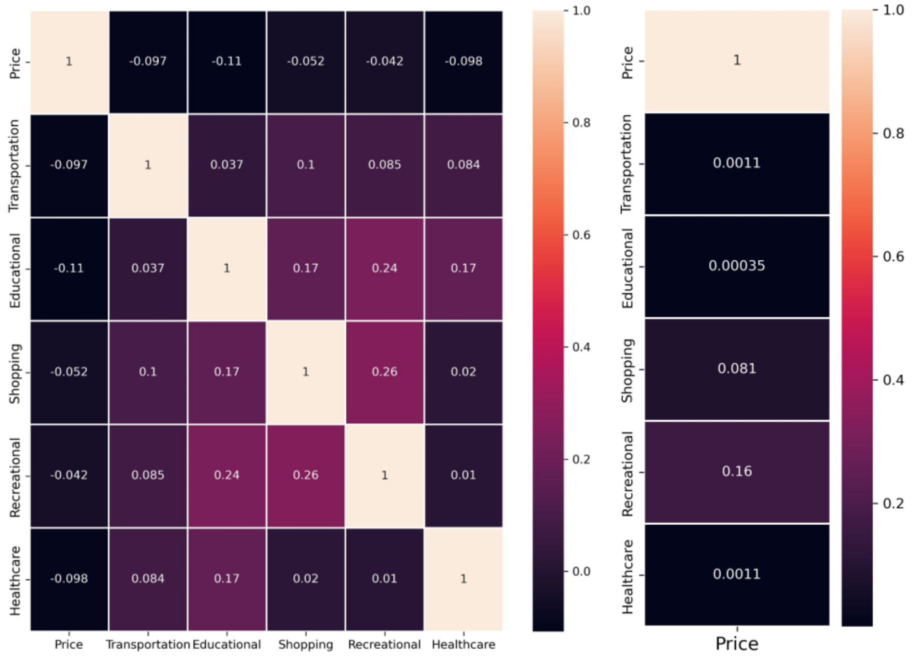

Figure 9. The results of correlation coefficients (left) and p-values (right) between house prices of central Beijing communities and their accessibility to different urban facilities.

Results indicate that house prices have little correlation with the accessibility to facilities as all the coefficients are below 0.11, meaning a negligible relation between them (Schober et al., 2018). In other words, lower-income residents do not have significantly worse accessibility than the higher-income groups. Moreover, the p-values between house prices and the accessibility to shopping and recreational facilities are above 0.05, indicating that they are unrelated. Thus, no evidence of spatial injustice has been found in the accessibility to facilities for central Beijing communities with different house price levels.

4.2. CASE STUDY OF SHANGHAI CITY

To further verify if the findings in Beijing are valid in other cities of China, this research conducts a comparative case study of Shanghai with the identical methods above. Similar to Beijing, as one of the biggest and most developed cities in China, Shanghai is also equipped with a wide range of urban facilities, and its central areas have equivalently high house price levels as well. This study concentrates on the central areas of Shanghai within its Inner Ring Road. As Shanghai is a highly economic-development-driven city, while Beijing has a solid political background in its urban planning, a comparative case study of these two cities can further help this research to evaluate the spatial justice in the accessibility to urban infrastructures in different cities in China.

4.2.1. The housing prices of communities in central Shanghai areas

With the dataset of 4227 communities, this study calculates the house prices' quartile values and divides them into four levels. The results of the boxplot analysis of central Shanghai communities are shown in Figure 10.
It indicates that the low house price level is below 70237, the low-to-medium is between 70237 and 90879, the medium-to-high is between 90879 and 119970, and the high level is above 119970 Chinese Yuan per square meter. Accordingly, the distribution map of these communities with different house price levels in central Shanghai areas is shown in Figure 11, where the dots in brighter colours represent communities with higher house prices.

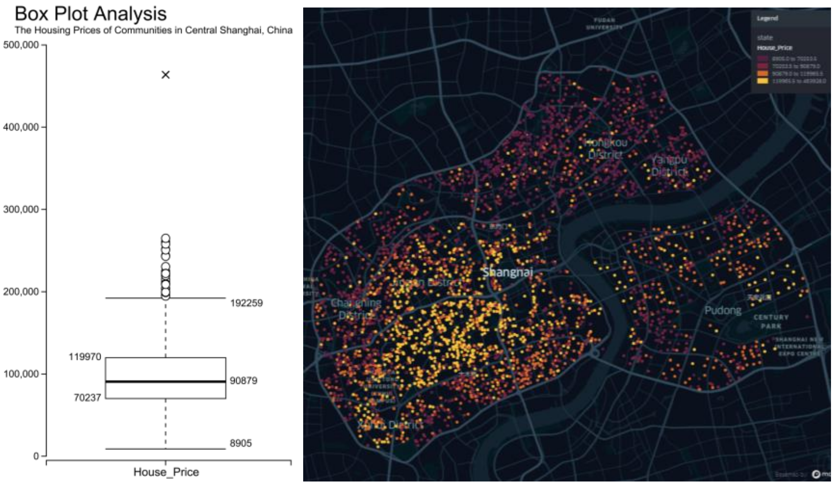

Figure 10: Left: The boxplot analysis of the house prices of central Shanghai communities, *Right:* The distribution map of the communities with different house price levels.

4.2.2. The accessibilities of central Shanghai communities to urban facilities

With the same methods above, this study investigates the relationship between house prices and the accessibility to urban facilities in various dimensions. The results are shown as follows: Figure 12 represents transportation facilities; Figure 13 refers to shopping amenities; Figure 14 concentrates on educational facilities; Figure 15 embodies health-care facilities; Figure 16 demonstrates recreational facilities.

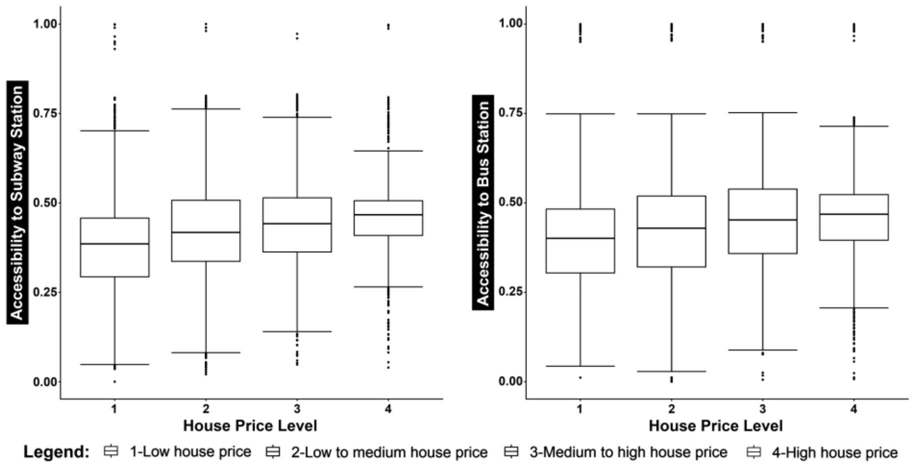

Figure 12. The boxplot analyses of the accessibility to public transportation facilities (subway and bus stations) for central Shanghai communities with different house prices.

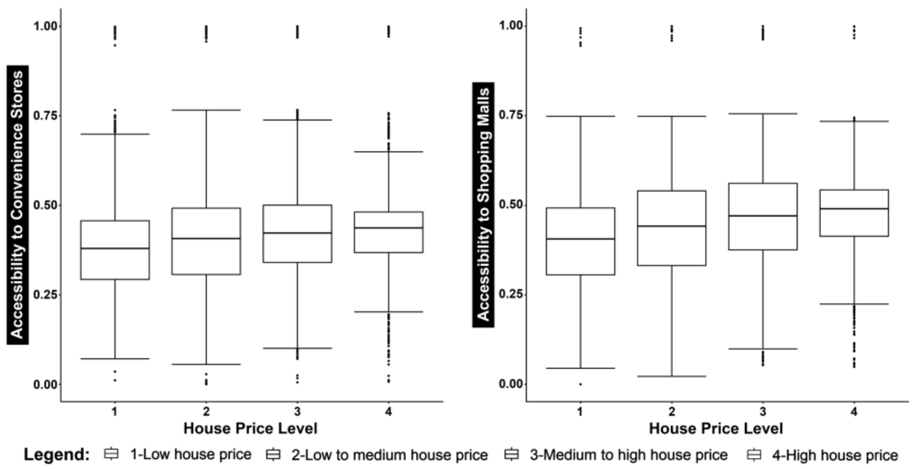

Figure 13. The boxplot analyses of the accessibility to shopping facilities (convenience stores and shopping malls) for central Shanghai communities with different house prices.

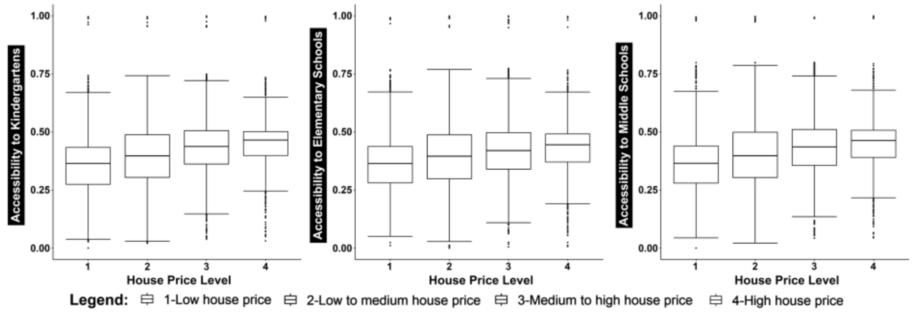

Figure 14. The boxplot analyses of the accessibility to educational facilities (kindergartens, elementary and middle schools) for central Shanghai communities with different house prices.

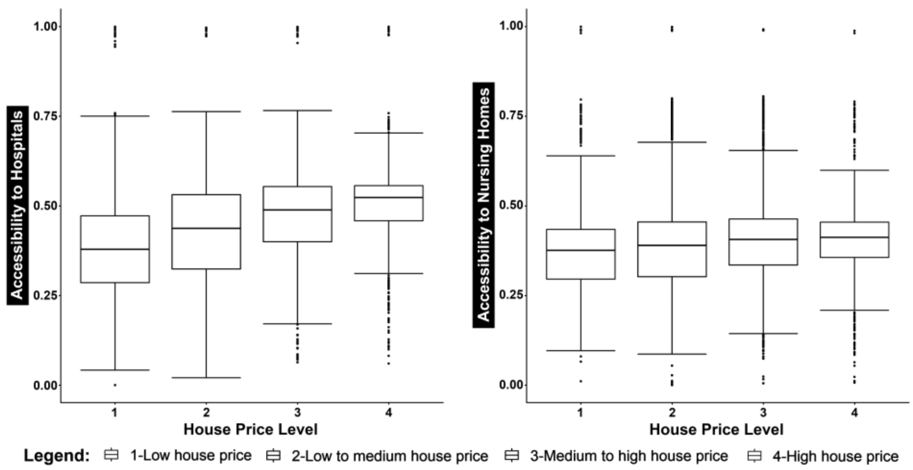

Figure 15. The boxplot analyses of the accessibility to health-care facilities (hospitals and nursing homes) for central Shanghai communities with different house prices.

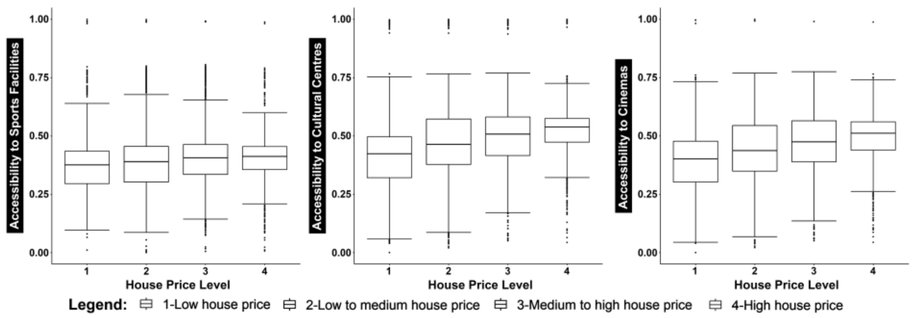

Figure 16. The boxplot analyses of the accessibility to recreational facilities (sports facilities, cultural centres and cinemas) for central Shanghai communities with different house prices.

The results above clearly show that as the community's house price increases, residents have better accessibility to urban facilities in all five dimensions of transportation, shopping, education, health care and recreation. These results suggest that people with higher income levels who live in communities with higher house prices can enjoy more convenience in accessing infrastructures in the city, which may indicate a potential spatial injustice for lower-income populations who live in communities with lower house prices. In other words, the analysis outcomes reveal that citizens with different incomes in central Shanghai do not have an equal approachability to urban amenities. However, as the figures above demonstrate, the gaps between communities of higher and lower house prices are not enormously large, indicating that such inequality may not be very severe. For example, looking into the median values of these communities' accessibility and house prices, this research found that the gaps between the lowest and highest house-price communities in their accessibility to transportation, shopping, educational and recreational facilities are within the range of 25%, varying from approximately 0.4 to 0.5 in their convenience indexes. In comparison, the differences in median values of their house prices between the lowest and highest are over 130%, changing from around 60,000 to 140,000 Chinese Yuan per square meter. In addition, the most significant inequality happens in the accessibility to hospitals, where the gap between the lowest and highest house-price communities is more than 40%, varying from around 0.38 to 0.54 in accessibility indexes, indicating that the government may need to put more efforts to provide more health-care facilities for people living in the lower house-price communities to reduce such urgent inequality.

4.2.3. Correlation analysis between the house prices of central Shanghai communities and their accessibility to urban facilities

To further look into the relations between house prices and the accessibility to urban facilities, this study conducts the correlation analysis and significance test to examine their Pearson linear correlation coefficients and the p-values. Results are shown in Figure 17, from which we can see that the correlation coefficients between house price and accessibility to various facilities are very small, as they are all below 0.3, indicating a very weak or negligible linear correlation between them (Schober and Schwarte, 2018). However, as shown in the right graph of Figure 17, their p-values are extremely small and very close to zero, indicating a significant relationship between house prices and the accessibility to urban facilities.

One possible interpretation of these coefficients and p-values is that the house price of a community has a close relationship with its accessibility to urban infrastructures, but this relation is not a simply linear connection, and it may have a more complex mathematical form, such as the non-linear high-degree polynomial function. In addition, the correlation coefficients between urban facilities in various dimensions are quite large and close to one, demonstrating a highly linear correlation between them, which may indicate these facilities are typically located in nearby areas. In other words, the facilities in central Shanghai may be distributed in gathering clusters, and the convenience of the accessibility to one facility may also indicate convenient access to others.

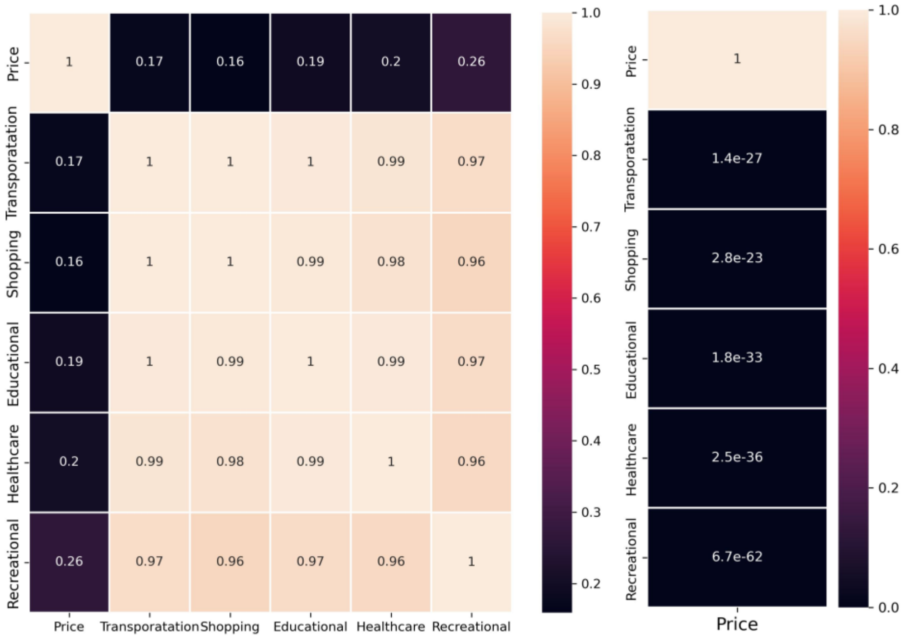

Figure 17. The results of correlation coefficients (left) and p-values (right) between house prices of central Shanghai communities and their accessibility to different urban facilities.

5. Conclusion and Discussion

5.1. MAIN FINDINGS AND CONCLUSION

This study evaluates spatial justice by analyzing the relationship between the house prices of communities and their accessibility to various facilities with big data analytic techniques. Through a comparative case study of the central urban areas in Beijing and Shanghai city in China, this research found quite different results of spatial justice in these two cities. In Beijing, which has been China's capital and political centre for more than 800 years (Zhao and Lyu, 2022), residents living in its central areas generally have relevantly equal access to various urban facilities, no matter how much the house prices of their communities are. Thus, spatial justice in central Beijing is maintained well by offering equal access to urban amenities for residents with different incomes. However, in Shanghai, which has been one of the most important economic centres in China since the reform and opening up policy in 1978 (Gu and Tang, 2016), its urban constructions are mainly driven by the economic development and the situation of spatial justice is quite different to Beijing case. Inhabitants of central Shanghai areas do not have equal access to urban facilities, as the communities with higher house prices typically have better access than the lower ones to facilities in all the five dimensions of transportation, shopping, education, health care, and recreation. The gaps in accessibility between the lowest and highest house-price communities are generally around 25%, and the most significant difference is in the accessibility to hospitals, where the gap is more than 40%. Such results demonstrate an apparent spatial injustice for people with lower income levels with respect to their accessibility to urban amenities, and the disparity between rich and poor is evident. As a result, this may indicate that policymakers should put more effort to refine the planning of infrastructures to reduce the inequality in accessing urban facilities.

The divergent outcomes of spatial justice in these two biggest cities in China may result from the different urban planning policies of these two areas. As the capital and political centre of China, which is an outstanding communist country in the world, Beijing may take the principle of equal rights for various citizens more important than economic development in urban construction. Therefore, it implements an equality-minded urban planning policy (Wu and Rowe, 2022), and the infrastructures of its central areas are relevantly equally distributed. In contrast, Shanghai is a city that has been concentrated on rapid economic development for decades (Zhang, 2003), and the ongoing growth of the urban economy plays a significant role in the urban planning of Shanghai (Zhang et al., 2011). Therefore, districts with higher economic development levels may be equipped with more urban infrastructures, and according to the laws of the economic market, the communities of these places can be sold at higher house prices. As a result, residents of these communities possess better accessibility to urban facilities than the citizens living in lower house-price areas. Such a spatial injustice may be a side effect of economy-driven urban construction. Urban planners and governmental policymakers have realized this problem and tried to implement a more sustainable urban planning policy to reduce inequality in the accessibility to facilities in recent years (Chen et al., 2020). As a result, although there is inequality between the higher and lower house-price communities in the accessibility to urban facilities, the gaps between the lowest and highest are usually within the range of 30%, while the gaps in their house prices are more than 130%, indicating that such inequality may not be extremely bad and unacceptable. With more attention and efforts put into this field, such spatial inequality may be further reduced.

In conclusion, Chinese cities may have a relevantly diverse situation regarding the relationship between house prices and the accessibility to infrastructures. In a city that concentrates more on political significance, such as Beijing, the relations between house prices and the accessibility to facilities are weak or negligible, and people with different income levels can generally have equal access to these amenities. In a city highlighting economic development, such as Shanghai, the relations between house prices and the accessibility to urban facilities are rather significant and may indicate an apparent spatial injustice in their accessibility to these infrastructures.

5.2. CONTRIBUTIONS AND LIMITATIONS

This study may provide a new understanding of the spatial justice in Chinese cities and offer references to urban planners and policymakers to create a more sustainable and equal spatial environment in China. In addition, it may provide a valuable and repeatable approach to examining spatial justice through the analysis of the relationship between house prices and the accessibility to urban infrastructures with big data techniques. Limitations mainly exist in the small number of case studies and the possible bias when collecting and dealing with the datasets, which may affect the generality of the research findings.

5.3. FUTURE RESEARCH DIRECTION

Future research can explore the relationship between house prices and the accessibility to urban facilities in other cities of China to examine if there are any common features of spatial justice in different cities in China. Moreover, investigating the spatial justice in the accessibility to urban facilities for other vulnerable groups such as children, aged and disabled people may be another direction worth attention. In addition, detecting the connection between house prices and the accessibility to facilities with advanced artificial intelligence methods, such as deep learning, may provide more practical suggestions to create a more equal and inclusive urban environment in cities.

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CITY DIVERSITY: HOW DO ARCHITECTURAL USES, AGES, AND STYLES AFFECT THE PUBLIC?

A case study in Manhattan through social media data

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Abstract. Jane Jacobs proposed that urban diversity yields numerous advantages, encompassing economic and cultural prosperity, heightened individual security, and augmented urban vibrancy. However, what is the specific correlation between city diversity and public sentiment? Does a higher level of diversity always result in a more positive public attitude? Our study endeavors to reassess Jacobs' theory of city diversity by leveraging urban data from multiple sources. Our research primarily concentrates on two categories of data. The first category pertains to city diversity data, encompassing building uses, building ages, and architectural styles, which were predicted through machine learning tools with image classification. The second category is public sentiment data collected from Twitter. We gathered tweets and measured the levels of positivity, negativity, and neutrality expressed by the public using natural language processing tools. Through spatial distribution analysis and correlation analysis of environmental and social media data, we revealed the relationship between city diversity and public sentiment. The results indicate that higher city diversity correlates with both more positive and negative sentiments among individuals, diminishing their neutral and indifferent attitudes in the Manhattan area. This serves to demonstrate that city diversity can exert a comprehensive influence on public sentiment, thereby validating and enriching Jane Jacobs' theory. Consequently, we advocate for a more nuanced and discerning approach towards city diversity within the context of contemporary urban agendas.

Keywords: *machine learning, building age, architectural style, building function, public sentiment.*

ملخص. اقترحت جين جاكوبس أن التنوع الحضري يؤدي إلى العديد من المزايا، بما في ذلك الرخاء الاقتصادي والثقافي، وزيادة الأمن الفردي، وزيادة الحيوية الحضرية. ومع ذلك، ما هي العلاقة المحددة بين تنوع المدينة والمشاعر العامة؟ هل يؤدي المستوى الأعلى من التنوع دائمًا إلى موقف عام أكثر إيجابية؟ تسعى دراستنا إلى إعادة تقييم نظرية جاكوبس حول تنوع المدن من خلال الاستفادة من البيانات الحضرية من مصادر متعددة. يركز بحثنا في المقام الأول على فئتين من البيانات. تتعلق الفئة الأولى ببيانات تنوع المدن، بما في ذلك استخدامات المباني وأعمارها والأنماط المعمارية، والتي تم التنبؤ بها من خلال أدوات التعلم الآلي مع تصنيف الصور. والفئة الثانية هي بيانات المشاعر العامة التي تم جمعها من تويتر. قمنا بجمع التغريدات وقياس مستويات الإيجابية والسلبية والحيادية التي عبر عنها الجمهور باستخدام أدوات معالجة اللغة الطبيعية. ومن خلال تحليل التوزيع المكاني وتحليل الارتباط لبيانات الوسائط البيئية والاجتماعية، كشفنا عن العلاقة بين تنوع المدينة والمشاعر العامة. تشير النتائج إلى أن ارتفاع التنوع في المدينة يرتبط بمشاعر أكثر إيجابية وسلبية بين الأفراد، مما يقلل من مواقفهم المحايدة وغير المبالية في منطقة مانهاتن. وهذا يساعد على إثبات أن تنوع المدينة يمكن أن يمارس تأثيرًا شاملاً على المشاعر العامة، وبالتالي التحقق من صحة نظرية جين جاكوبس وإثرائها. وبالتالي، فإننا ندعو إلى اتباع نهج أكثر دقة وتمييزًا تجاه تنوع المدن في سياق جداول الأعمال الحضرية المعاصرة.

الكلمات المفتاحية: *التعلم الآلى، عمر المبنى، الطراز المعمارى، وظيفة المبنى، مشاعر العامة.*

1. Introduction

Big cities can flourish by embracing diversity, which encompasses districts of various functions, streets of limited lengths, buildings of diverse conditions, and a populace with varied purposes and backgrounds, as is repeatedly claimed by Jane Jacobs (1961). She suggested that city diversity fosters the emergence of a wide range of industries and a diverse population, which injects vibrancy into the streets. Conversely, the absence of diversity not only contributes to feelings of monotony and inconvenience among individuals but also leads to a decreased sense of security (Jacobs, 1961). This is exemplified by the comparison of Fifth Avenue and Park Avenue, where the combination of buildings of all conditions appears more appealing to people as the mingling of diverse ages, styles, and uses of buildings implies different economic values as well as aesthetic and technological tastes.

Jane Jacobs' theories have garnered extensive discussion and application in contemporary urban practice to create a more humanistic and vibrant city (Alizadeh, 2015; Marguerite van den Berg, 2018). A growing body of research has also emerged, employing high-resolution techniques to quantify and validate her principles (Sung et al., 2015). However, most of these studies have tended to prioritize the analysis of built environments, often overlooking the crucial relationship between city diversity and the subjective perceptions of urban residents. Therefore, our study seeks to revisit Jane Jacobs' theory by integrating an analysis of city diversity, with a specific emphasis on the diversity associated with buildings, alongside sentiment analysis of social media data extracted from Twitter. Geotagged social media platforms, such as Twitter, provide a wealth of textual data that enables us to analyze both the tangible and intangible impacts of the urban environment on individuals (Abdul-Rahman et al., 2021). They possess the potential to quantify subjective interpretations of urban environments (Katja Thömmes and Ronald Hübner, 2018).

The methodology proposed in this study involves the following steps: 1) Obtaining city diversity data on building uses and ages to understand their spatial distribution characteristics; 2) Acquiring street view images (SVI) of building facades and utilizing machine learning models for architectural style prediction; 3) Collecting social media data from platforms such as Twitter and conducting text sentiment analysis; 4) Integrating the urban built environment data with the social media sentiment data to perform spatial distribution and correlation analysis.

2. Literature Review

2.1. CITY DIVERSITY

According to Jane Jacobs, city diversity is an inherent characteristic of cities and encompasses several elements, such as a mix of land uses, small block sizes, a variety of buildings in different conditions, and a concentration of people (Jacobs, 1961). Despite facing criticism (Mumford, 1962), Jacobs' theory has emerged as a significant component of contemporary urbanism. Glaeser et al. (2001) discussed the "four particularly critical amenities" for the livability of a city, with the presence of a wide variety of services and consumer goods being the most obvious. Fainstein (2015) advocated for diversity as a central guiding principle for urban planners. Moreover, researchers have conducted comparative analyses of the advantages and disadvantages associated with urban specialization and diversification at various scales (Duranton and Puga, 2000).

Recently, with technological advancements, an increasing number of studies are attempting to quantitatively validate Jacobs' theory from different perspectives. Scholars from Italy (De Nadai et al., 2016) validated Jacobs' four elements of diversity using mobile phone activity data. Powe et al. (2016) used spatial regression models to compare and analyze four cities in the United States, highlighting the importance of old buildings for economic development. Satellite imagery and deep learning have been employed to study city diversity and predict urban vitality based on the four principles (Šćepanović et al., 2021). The contribution of diversity to urban economies has also been quantified based on the quantity and types of shops on city streets (Yoshimura et al., 2022).

2.2. SOCIAL MEDIA DATA

Previous research has extensively investigated the potential of leveraging social media data within urban contexts, recognizing their applicability in interpreting urban environments and addressing challenges related to subjective quantification (Honig and MacDowall, 2017; Katja Thömmes and Ronald Hübner, 2018; Pfeffer et al., 2018). Chen et al. (2016) employed APIs from platforms such as Crunchbase, Yelp, Flickr, and Twitter to discern quantitative factors contributing to the growth of innovation hubs in cities like Boston and Cambridge. While Flickr and Twitter were used to identify activity and geolocation trends, Crunchbase was used to map innovation hubs, and Yelp helped to illustrate amenity density and categories, offering insights into the characteristics driving innovation hub presence. Notably, this approach didn't delve into user-contributed content, missing the potential for emotion-driven placemaking. Rossi, Boscaro, and Torsello (2018) centered their investigation on Instagram, creating a tourism-focused analysis of Venice through geotagged image classification. The resulting heatmap visualized tourism patterns by comparing classified photos with geolocation distribution. Nevertheless, textual content analysis was not incorporated into their study. More recently, Jang and Kim (2019) showcased the value of Instagram hashtags in extracting identity-related insights for understanding urban identity across culturally distinct but historically similar cities in the Seoul metropolitan area. This work emphasized the utility of crowd-sourced data from social media platforms for more accurate urban mapping. As for Urban Emotions, Kim (2020) introduced social media as an analytical tool to enhance public policy-making through emotion analysis, offering deeper insights into the built environment and fostering informed citizen-decision-maker conversations.

3. Research Framework and Site

3.1. FRAMEWORK

As depicted in the framework, we integrated an analysis of city diversity, which encompasses building ages, building uses, and architectural styles, with sentiment analysis of social media data from Twitter. (Figure 1).

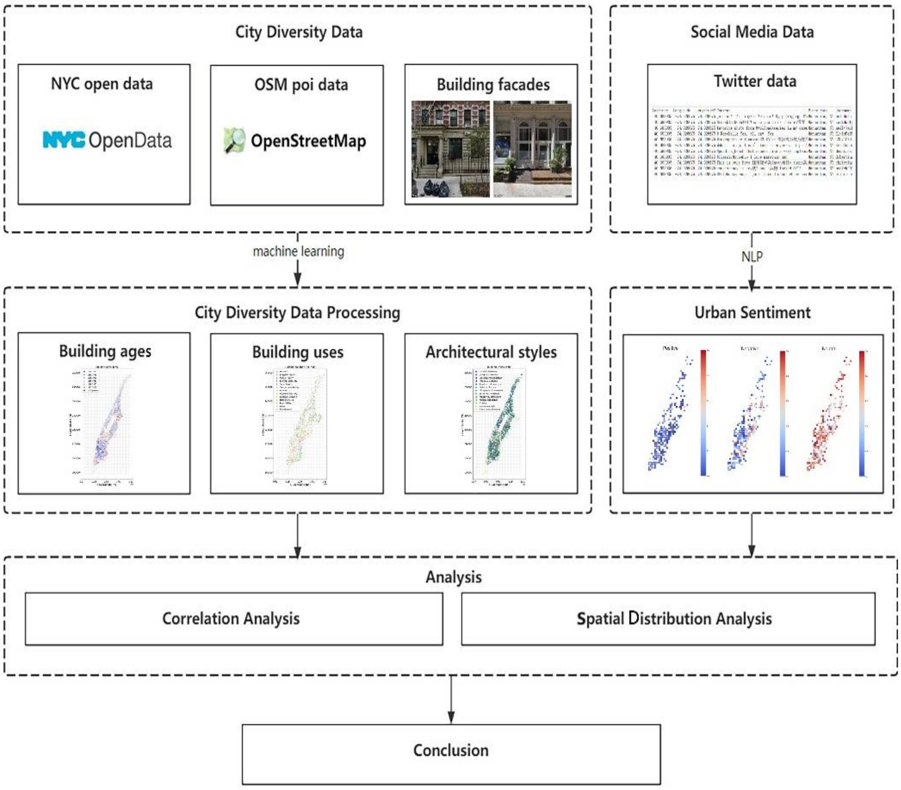


Figure 1. Research framework.

3.2. RESEARCH SITE

Manhattan, as the most densely populated borough and the economic center of New York, holds significant research value in city diversity and is frequently referenced in discussions of urban planning, including the influential work by Jacob Jacobs (Jacobs, 1961). Furthermore, Manhattan's architecture presents a wide range of characteristics that make it an ideal subject for analyzing city diversity. The grid-like street layout and intricate road network have contributed to the development of a diverse array of urban functions (Koolhaas, 2014). It also encompasses buildings from different eras, showcasing architectural styles that span from classical to postmodern. Moreover, due to the limited availability of land resources here, many buildings take on a narrow and elongated form. As a result, the street facades often exhibit exquisite design and reflect the architectural characteristics of that era (Eschenasy, 2021).

4. Data and Methods

The data used in this study can be divided into two categories. The first category is city diversity data, which includes the function of buildings (i.e., Point of Interest, POI), the age of buildings (i.e., data on the year of construction), and the architectural style exhibited by the street facades of buildings. The second category is social media data from Twitter. We primarily analyze the textual content posted on Twitter by individuals when they are located in Manhattan. Through this analysis, sentiment analysis scores are derived for each post, which indicates the level of positivity, negativity, or neutrality expressed within the content.

4.1. CITY DIVERSITY DATA

4.1.1. Building Uses

The data on building uses primarily comes from the NYC Open Data website, and the POI data employed in this study is updated until July 2023. We filtered the data based on the “BOROUGH” field, selecting entries where the value is 1, representing Manhattan. This filtering process resulted in a total of 5,855 valid building POI data points specific to Manhattan.

4.1.2. Building Ages

The building age data also comes from the Building Footprints dataset provided by NYC Open Data. This dataset includes top-view polygon outlines, geographic location points, construction years, and other attributes for each building in New York City. It has been consistently updated weekly since 2016. The data used in this study is updated until May 2023. After removing irrelevant fields and filtering out entries where the first digit is 1, we obtained a total of 45,437 valid data entries representing buildings in Manhattan. The construction year of each building is represented by the ‘cnstrct_yr’ field.

To facilitate a more practical and meaningful analysis, the study categorized the building ages into seven distinct periods. The categorizations were based on a comprehensive understanding of the urban and architectural development history of Manhattan, as well as insights derived from relevant literature by architectural historians (Roth and Clark, 2016). These age periods are as follows in TABLE 1:

TABLE 1. Building ages

Label	Building age period	Features
0	1690-1865	the age of innovation based on tradition
1	1865-1885	the age of expanding economy
2	1885-1915	the age of order
3	1915-1940	the age of nostalgia and avant-garde
4	1940-1973	the age of American modernism
5	1973-2001	the age of modernism and alternatives
6	2001-present	— —

4.1.3. Building Styles

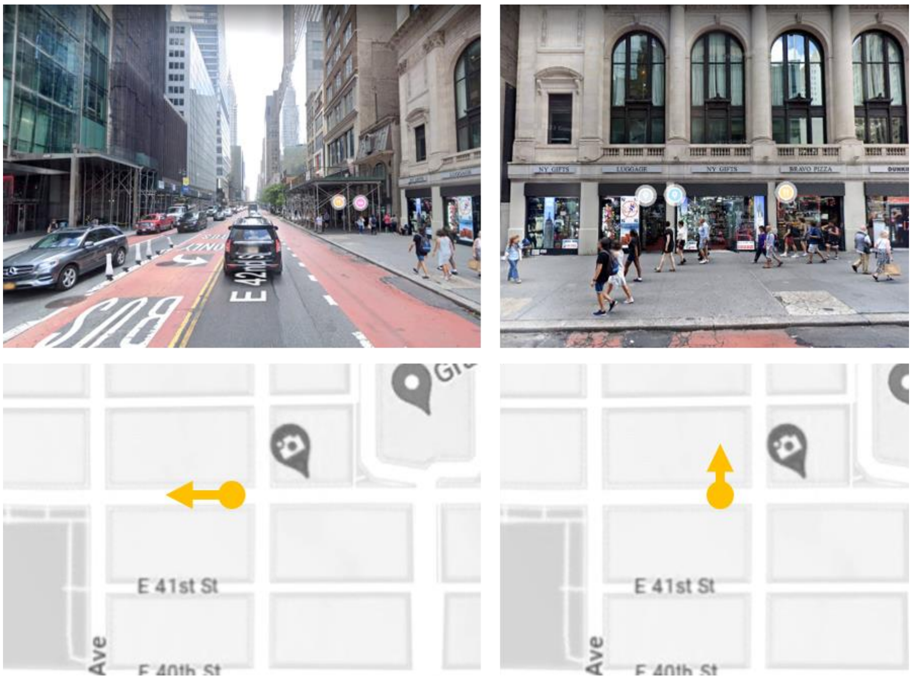
The dataset of architectural styles in Manhattan was compiled through a two-step process that involved obtaining street view facade images and applying machine learning techniques for style prediction. The process can be summarized as follows:

a) Collecting SVI of Architecture Facade

The street view images (SVI) used in this study are obtained from the service provided by Google (Anguelov et al., 2010). However, it is important to note that the required SVI for this research should present the buildings' front facades in an upright position (Figure 2. b), unlike the default view of Google SVI (Figure 2. a).

To address this, we projected the points representing each building from the building footprint files onto the nearest street. After obtaining the street projection points for each building, we calculate the angle between the vector formed by the 'projection point-building point' and the north vector (Sun et al., 2022). This angle serves as an adjustment parameter for the street view camera, allowing us to obtain SVI that directly faces the corresponding building's facade.

This approach ensured that each building had a corresponding SVI, as opposed to using a method that obtained SVI at fixed intervals, which would not be matched with each building individually. Furthermore, the SVI obtained closely resembled an upright perspective, minimizing the impact of perspective and tilt on the prediction of facade styles.



a *b*

Figure 2. Street view image from different perspectives

b) Training Style Prediction Model

For the training of the prediction model, we selected the Architecture Dataset available on Kaggle as the initial training set for architectural styles. Considering the distinctive architectural styles in Manhattan, we first filtered and categorized the styles into 13 labels (TABLE 2), representing 13 styles in chronological order. In each style label, we selected at least 200 images that closely resemble building facades for training. These images were organized into separate folders for each style category, and the dataset was further divided into training, validation, and testing sets.

To ensure consistency and minimize the impact that the dataset has on training accuracy, we preprocessed the images to have the same dimensions and pixel values. Then, we utilized the DenseNet-121 model, which is a deep learning model built into PyTorch, to conduct the training and prediction process. DenseNet-121 performs well even with limited data and can capture fine details in images, making it suitable for image classification tasks (Huang et al., 2017).

TABLE 2. Architectural styles

Label	Architecture style
0	Colonial architecture
1	Georgian architecture
2	Greek Revival architecture
3	Palladian architecture
4	American craftsman style
5	Gothic architecture
6	Chicago school architecture
7	Beaux-Arts architecture
8	Art Nouveau architecture
9	Art Deco architecture
10	Brutalism
11	International style
12	Postmodern architecture

4.2 TWITTER DATA

In terms of urban sentiment, we analyzed textual data from social networks, specifically Twitter, using natural language processing (NLP) (Tusar and Islam, 2021) techniques to obtain corresponding positive, negative, and neutral sentiment scores. By conducting a comprehensive analysis of the content posted by a large number of users on social media, we can capture people's true emotional states and sentiment tendencies (Gao et al., 2022). This analysis will help us explore the differences in emotional perception among urban residents in different built environments.

4.2.1. Obtaining Twitter Data

Twitter, being a global social media platform, aggregates real-time comments and expressions from a large number of users, providing meaningful data for understanding the perceptions of residents in Manhattan.

We chose snsscrape to retrieve 40,000 Twitter data entries from Manhattan over the course of one week (Qi and Shabrina, 2023). These data points encompass various useful attributes such as tweet posting time, tweet ID, latitude, longitude, tweet content, place name, and user name. The comprehensive information derived from these attributes will provide us with a detailed understanding of resident sentiment in different periods and spatial locations within the Manhattan area.

4.2.2. Analyzing People's Sentiment Tendency

By employing NLP techniques, we can perform sentiment analysis on a large volume of Twitter text content, accurately identifying positive, negative, and neutral sentiments within them, and providing valuable sentiment labels for urban sentiment assessment.

We utilized the TweetNLP library for sentiment analysis (Camacho-Collados et al., 2022). TweetNLP is an NLP tool specifically developed for social media text, taking into consideration Twitter's unique text characteristics such as abbreviations, spelling errors, emoticons, and more, enabling better handling of Twitter data.

As a result, we obtained sentiment labels (positive, negative, or neutral) and their corresponding scores for each tweet. The presence of both negative and positive sentiments in a city reflects the richness of urban emotions (Resch et al., 2015) and serves as an expression of urban vitality (Siriaraya et al., 2023). By visualizing these scores, we can create sentiment trend graphs, revealing spatial patterns of emotional changes within Manhattan. Additionally, these sentiment scores provide data support for subsequent correlation analysis, facilitating a better understanding of the emotional characteristics and differences among populations in diverse urban environments (Drus and Khalid, 2019).

4.3. DATA PREPROCESSING

4.3.1. Data Cleaning and Spatial Distribution

After removing invalid values and standardizing the coordinates, we proceeded to visualize the two categories of data. Then, we created a 1000 feet * 1000 feet analysis grid for Manhattan and aligned the data on city diversity (building uses, building ages, architectural style) and Twitter data with the analysis grid for further data processing and correlation analysis.

TABLE 3. Data normalization result examples

Index	**City Diversity**					**Sentiment tendency on social media**		
grid_id	**grid_ bvld**	**grid_period _count**	**grid_style _count**	**grid_poi _num**	**grid_poi _type**	**positive**	**negative**	**neutral**
1317	0.369	0.667	0.727	0.127	0.625	0.015	0.272	0.811
1664	0.302	0.667	0.909	0.164	0.625	0.015	0.238	0.839
1271	0.079	0.667	0.636	0.164	0.500	0.549	0.003	0.472
1310	0.738	0.833	1.000	0.055	0.375	0.073	0.039	0.944
1272	0.714	0.667	0.909	0.200	0.625	0.061	0.003	0.986
……			……			……		

4.3.2. Data Selection and Normalization

For each spatial grid, we calculated the following factors: the number of buildings within the grid (grid_bvld), the number of architectural styles (grid_style_count), the number of building age periods (grid_period_count), the number of POI (grid_poi_num), the number of types of POI (grid_poi_type), and the average values for negative, neutral, and positive sentiments (For each grid, we did not calculate the number of architectural styles and building ages as they align with grid_bvld, and we did not calculate the number of each sentiment type because the mean score provides more meaningful information.).

To eliminate differences in scale between these features and facilitate subsequent correlation analysis, we normalized the aforementioned data (TABLE 3.).

4.4. DATA ANALYSIS

4.4.1. Correlation Analysis on City Diversity Indicators

To understand the spatial distribution characteristics of factors related to city diversity concerning buildings and their interrelationships, we conducted a correlation analysis on the following five factors: grid_bvld, grid_style_count, grid_period_count, grid_poi_num, and grid_poi_style. These factors are associated with building uses, building ages, and architectural styles.

4.4.2. Correlation Analysis on City Diversity and Twitter Sentiment Data

To understand the relationship between built environment diversity and the subjective perceptions exhibited by urban residents on social platforms, we conducted a correlation analysis between five factors representing diversity and four factors representing subjective perceptions within each spatial grid.

5. Results and Discussion

5.1. DATA VISUALIZATION

5.1.1. Visualization of Building Uses

In Manhattan (Figure 3), the two most prevalent building uses are education and recreation, accounting for approximately 16.67% and 16.65% respectively. The distribution of educational facilities is relatively balanced, with concentrated areas in the northwest corner and southern part of Central Park. Recreational facilities are relatively dense in the central and northern parts of Manhattan. The distribution of residential area, however, is uneven, primarily concentrated in the northeast and southeast regions of Manhattan. Transportation-related facilities mainly exhibit a surrounding distribution along the inner areas of Manhattan.

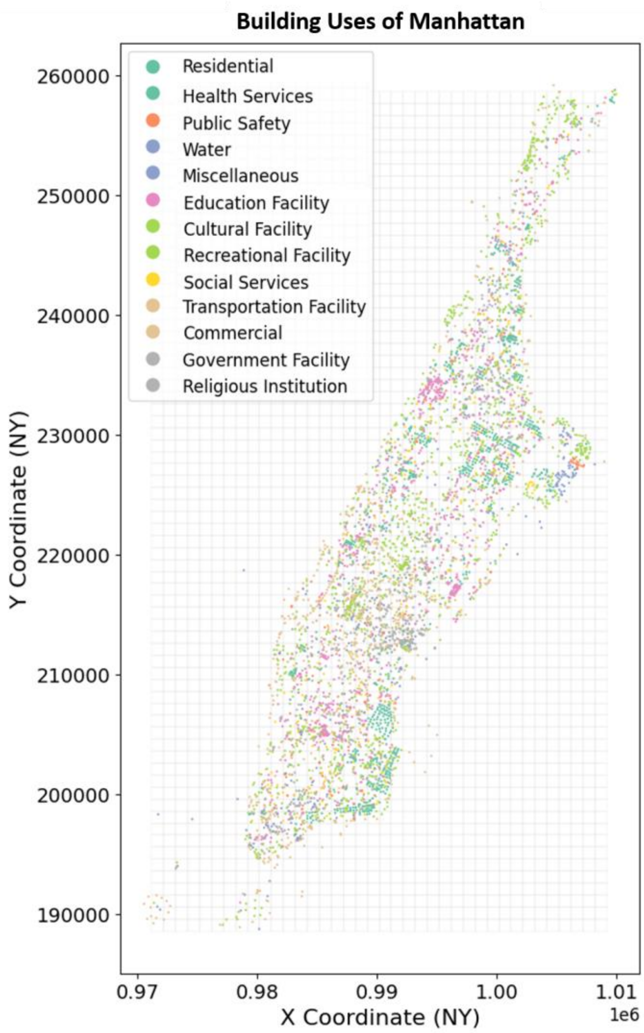


Figure 3. Building uses distribution

5.1.2. Visualization of Building Ages

The oldest buildings, constructed between 1690 and 1865, are primarily located in the southern part of Manhattan, aligning with the historical development of the first settlement established by the Dutch in this area. The most prevalent building age is between 1885 and 1915, during which buildings were densely distributed throughout Manhattan. In the 21st century, new construction projects are mainly concentrated in the northern part of Central Park and the southern region of Manhattan (Figure 4).

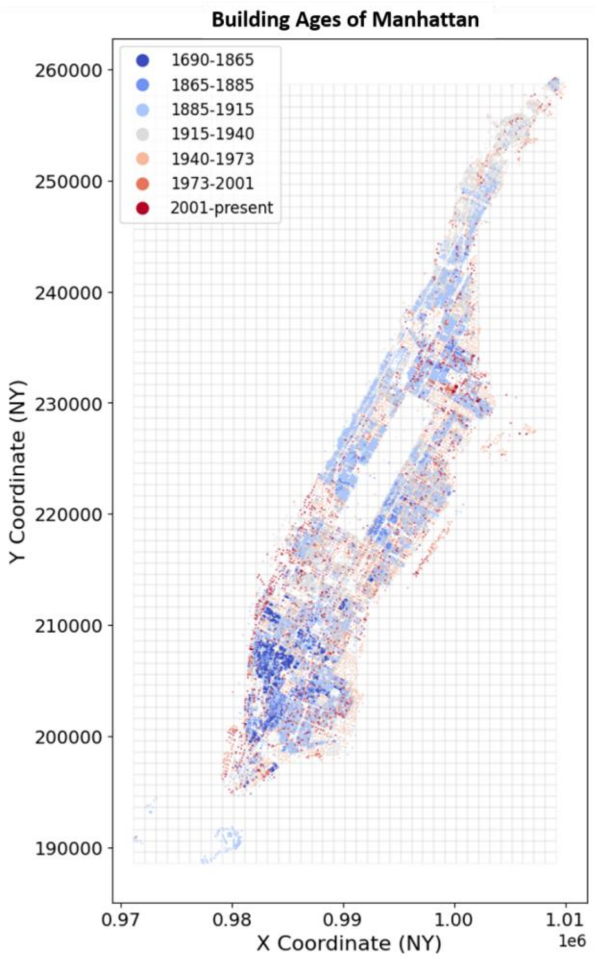


Figure 4. Building ages distribution

5.1.3. Visualization of Architectural Styles

a) Accuracy of Prediction Model

After multiple rounds of training, our model achieved an accuracy of 99.91% on the training set and 78.39% on the validation set. The prediction accuracies for each style on the validation set are shown in Figure 5. Recognizing architectural styles accurately poses certain difficulties, and in this study, the main objective of architectural style prediction is to differentiate styles among buildings and obtain a diversity of architectural styles within a specific region, rather than accurately identifying the architectural style of each building. Therefore, we consider this model suitable for style prediction.

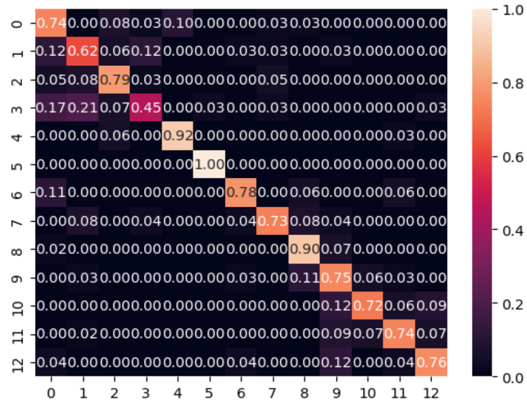


Figure 5. Accuracy matrix of prediction model

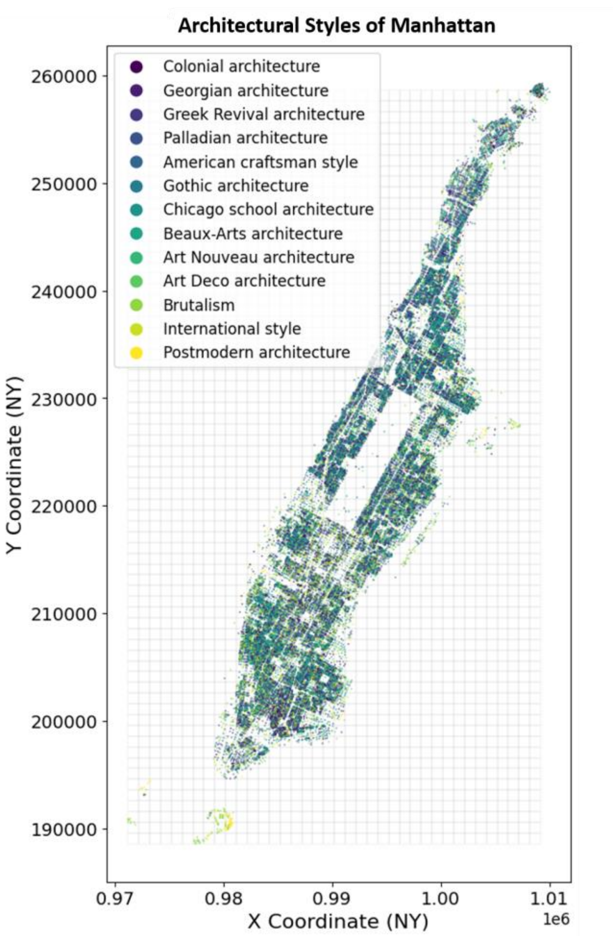


Figure 6. Architectural styles distribution

b) Visualization of Style Prediction

After excluding invalid images (such as those with empty or damaged images, or buildings heavily obscured), we applied the trained model to predict architectural styles in Manhattan (Figure 6).

The most prevalent historical architectural style is Georgian, accounting for approximately 18.24%, and it is widely distributed across the entire island. This architectural style gained popularity during the colonial period in the United States due to its elegant and symmetrical design, and gradually became a significant part of the city's historical heritage and unique architectural landscape. International modern architecture represents approximately 15.86% of the buildings in Manhattan and is also widely distributed throughout the island. This indicates that Manhattan is a metropolis where modernity and history coexist and intertwine. There are no distinct architectural style zones, but rather a blending of old and new, showcasing the coexistence of modernity and history.

5.1.4. Visualization of Twitter Sentiment

Based on the grid division, we calculated the average scores of urban emotions and visualized the results (Figure 7). However, due to the collection of Twitter data lasting within only one week and the presence of data overlap, some areas may not be displayed in the visualization. Regarding the overall distribution of urban emotions, the results show that the overall sentiment distribution is characterized by a higher proportion of neutral emotions followed by negative emotions and positive emotions. Specifically, the distribution of negative emotions is more concentrated in the southeastern area of the city.

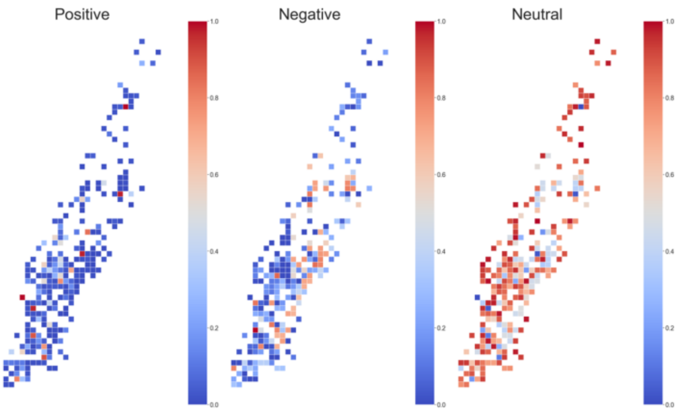


Figure 7. Twitter data distribution

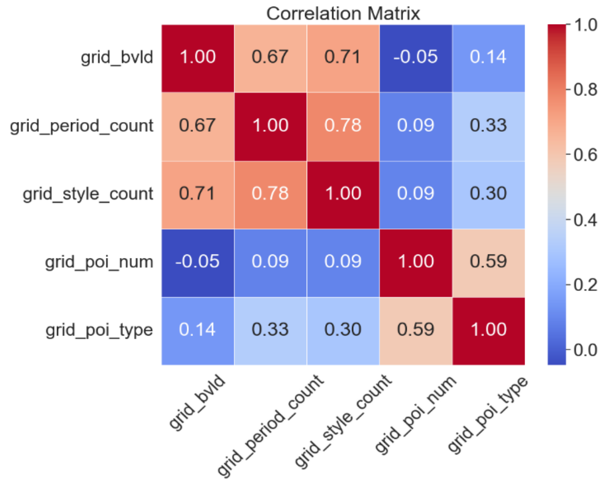


Figure 8. Pearson correlation coefficient of city diversity factors

TABLE 4. P-value of city diversity factors

	grid_bvld	**grid_period_count**	**grid_style_count**	**grid_poi_num**	**grid_poi_type**
grid_bvld	1.00	5.05e-33	1.56e-39	4.63e-01	2.43e-02
grid_period_count	5.05e-33	1.00	5.41e-52	1.71e-01	1.10e-07
grid_style_count	1.56e-39	5.41e-52	1.00	1.63e-01	1.75e-06
grid_poi_num	4.63e-01	1.71e-01	1.63e-01	1.00	3.82e-24
grid_poi_type	2.43e-02	1.10e-07	1.75e-06	3.82e-24	1.00

5.2. CORRELATION ANALYSIS

5.2.1. Correlation Analysis of City Diversity Factors

We employed a significance level of P-value < 0.05 to determine statistically significant correlations, which we denoted with an asterisk (*) in the table. Our analysis revealed significant positive correlations between grid_bvld, grid_period_count, grid_style_count, and grid_poi_style. Additionally, there was a significant correlation between grid_poi_num and grid_poi_type.

Interestingly, our examination (Figure 8) unveiled that an increase in the diversity of building ages and architectural styles did not yield a significant impact on the number of points of interest (POI), but it did have an impact on the variety of POI. This finding aligns with Jane Jacobs' theory that different building conditions engender diverse economic values, thereby contributing to the proliferation of businesses and the prosperity of streets.

5.2.2. Analysis of City Diversity and Twitter Sentiment Tendency

To investigate the correlation between three sentiment tendencies (positive, negative, neutral) and city diversity factors, we initially identified the grids that contained data for both categories. Utilizing the grid division, we computed the linear correlation coefficients and p-value between the sentiment tendencies (positive, negative, neutral) and various city diversity factors within each grid. Subsequently, we employed a heatmap visualization of the correlation matrix to facilitate further analysis.

a) The relationship between Positive Scores and City Diversity

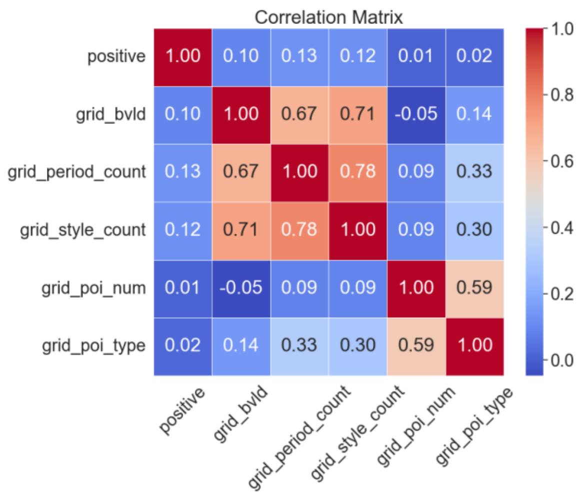


Figure 9. Pearson correlation coefficient of city diversity and positive sentiment

TABLE 5. P-value of city diversity and positive sentiment

	positive
positive	1.000
grid_bvld	0.132
grid_period_count	0.038*
grid_style_count	0.048*
grid_poi_num	0.923
grid_poi_type	0.767

The positive score exhibits a significant correlation with the diversity of building ages and architectural styles, while its correlation with the number and diversity of building uses is not evident (TABLE 5). Within each analysis grid (Figure 9), as the diversity of building ages and architectural styles increases, there is a corresponding increase in the positive tendency scores of the urban population. This finding aligns with Jacobs' belief that city diversity plays a crucial role in preventing monotony in streets, making them more engaging and vibrant for people (Jacobs, 1961).

b) The Relationship between Negative Scores and City Diversity

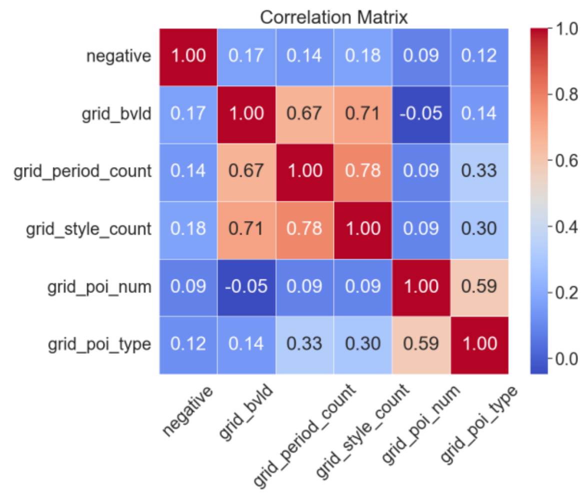


Figure 10. Pearson correlation coefficient of city diversity and negative sentiment

TABLE 6. P-value of city diversity and negative sentiment

	negative
negative	1.000
grid_bvld	0.00847*
grid_period_count	0.0238*
grid_style_count	0.00613*
grid_poi_num	0.171
grid_poi_type	0.0629

The negative score is significantly correlated with the number of buildings, the richness of architectural styles, and the diversity of building ages. However, its correlation with the number and richness of building uses is not evident (TABLE 6). it is noteworthy that the negative emotional tendency is strongly correlated with the richness of building ages (Figure 10). This suggests that we should not blindly idolize classical architectural styles and assume that the mere diversity of buildings will automatically bring happiness and positivity to urban citizens.

While a combination of various architectural styles can enhance the interest of a street, an excessive diversity of architectural styles, particularly without proper planning and design, may lead to visual dissonance and frustration. It is important to consider that the architectural style labels used in this context primarily consist of historical architectural styles. Therefore, a neighborhood with diverse architectural styles may indicate a higher concentration of older buildings with relatively poor living conditions. Although such neighborhoods may appear aesthetically pleasing, they may have lower livability, leading to a higher likelihood of negative emotions among residents.

This highlights the need for adequate city diversity. It should not solely rely on spontaneous formation, as it may result in spatial inequality. Therefore, scientific and rational design interventions are necessary to ensure a well-balanced urban environment.

c) The Relationship between Neutral Scores and City Diversity

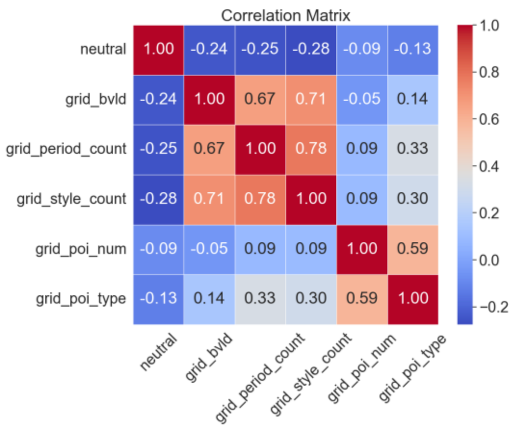


Figure 11. Pearson correlation coefficient of city diversity and neutral sentiment

TABLE 7. P-value of city diversity and neutral sentiment

	neutral
neutral	1.000
grid_bvld	0.000122*
grid_period_count	0.000052*
grid_style_count	0.000011*
grid_poi_num	0.180
grid_poi_type	0.0481*

The neutral emotional tendency is significantly correlated with the number of buildings, the richness of architectural styles and ages, and the variety of building uses in an opposite manner (TABLE 7). In areas with dense buildings, diverse architectural styles, building ages, or uses, the neutral emotional tendency of urban citizens significantly decrease, while the positive or negative emotional tendencies will likely increase (Figure 11).

This suggests that city diversity does contribute to increasing the activity level of urban citizens, whether it manifests as positive or negative emotions. This decrease in neutrality implies a reduced indifference towards the city, potentially leading to more interactions and possibilities. It also helps to alleviate monotony and dullness, ultimately enhancing urban vitality. As Jacobs claims, there is no greater sign of urban decline and lifelessness than a lack of diversity and vibrancy within city blocks (Jacobs, 1961).

5.3. DISCUSSION

The factors influencing the sentiment tendency of individuals primarily include the number of buildings, the richness of architectural styles, the diversity of building ages, and the variety of building uses. Among these four factors, the richness of building ages and architectural styles show a positive correlation with both positive and negative emotions, while the number of buildings, the richness of architectural styles, and the diversity of building ages and uses have a negative correlation with neutral emotions. It suggests that city diversity has a positive impact on the emotional state of individuals as they present different historical, cultural, and aesthetic elements, arousing curiosity and interest while alleviating neutral and indifferent emotions. However, it is important to be cautious about excessive city diversity, as it can lead to issues such as a decline in the quality of public spaces on streets, varying living conditions, and spatial inequality, which can trigger negative attitudes.

This echoes Jane Jacobs' theory that the blending of building of all conditions can eliminate the monotony of urban streets and promote the generation of differentiated activities and sentiments among people in the city. Still, we need to maintain a balanced and cautious attitude rather than blindly advocating for city diversity so that it will help create a more positive urban emotional atmosphere. Moreover, it is important to note that the purpose of city diversity is not solely to evoke positive attitudes. Negative sentiments can also contribute to city vibrancy. Ultimately, it is the richness derived from human diversity that brings vitality and colors to the urban environment, as emphasized by Jacobs (Jacobs, 1961).

6. Conclusions, Limitations, and Future Research

This study utilized machine learning techniques and analyzed multiple data sources to investigate the impact of city diversity, represented by building uses, ages, and styles, on public sentiment. The results indicate that the number of buildings, the diversity of building ages, and architectural styles are positively correlated with both positive and negative public sentiment while exhibiting a significant negative correlation with neutral sentiment. These findings provide initial support for Jane Jacobs' theory of city diversity. However, the study also identified certain limitations of her theory. For instance, positive and negative emotions are not always mutually exclusive; they may increase simultaneously with the increase of city diversity, while a noticeable decrease is observed in neutral or indifferent attitudes towards the city.

This study introduced a methodology that integrates technological advancements with classical urban design theories, allowing for a reflection on these theories in a contemporary context. It holds potential researchers to delve into the specific geographical and cultural attributes of each city, uncovering their distinct characteristics and relationships with individuals.

Additionally, this study provides valuable insights into urban design by offering data-driven conclusions on evaluating public sentiment tendencies. It offers recommendations on how to strike a more nuanced balance in city diversity to enhance urban vitality and foster positive engagement among city residents. These findings can inform urban planners and designers in making more informed decisions and creating environments that cater to the diverse needs and preferences of the urban population.

However, it is important to acknowledge the limitations of this study. Firstly, the exploration of Jane Jacobs' theory of city diversity primarily focused on the aspect related to buildings, neglecting other factors such as street length, demographic diversity, and neighborhood facilities. Future research should aim to investigate Jacobs' theory from a more comprehensive perspective.

Secondly, the sentiment data used in this study was derived from the Twitter platform within a one-week timeframe. This approach has limitations as the expression of emotions on social media may not be entirely accurate or can be influenced by biases. Moreover, relying solely on Twitter data may introduce a bias, as Twitter users might not represent the entire population, and sentiment analysis through Twitter might not capture the full range of public feelings or accurately interpret the nuances in public opinion.

Additionally, this study focused solely on the Manhattan area in New York as the research site. Other cities may exhibit variations in the relationship between city diversity and public sentiment. Therefore, further research is needed to validate and generalize the findings across different urban contexts.

Moreover, regarding data processing, although the predictive model for architectural styles demonstrated good performance on the validation set, the accuracy of the model may still have room for improvement due to sample selection and the limited volume of available data.

These limitations highlight the need for continued exploration. For future research, it is beneficial to expand the scope of the study by including a wider range of cities and considering various aspects of city diversity. This will enhance the generalizability of the research findings and provide a more comprehensive understanding of the topic. Additionally, incorporating additional data sources, such as sensor data and crowd mobility data, can provide a more comprehensive analysis of the impact of various city diversity factors on public sentiments. This approach will facilitate a deeper understanding of the relationship between the quality of urban public spaces and the emotions experienced by urban populations. Moreover, it is recommended to explore more advanced machine learning and sentiment analysis techniques. By incorporating these advanced techniques, the accuracy of the analysis results can be enhanced. These advancements in research methodology and data analysis will contribute to a more robust and nuanced understanding of the relationship between city diversity and public sentiment. Ultimately, this knowledge can inform the development of effective strategies and interventions for creating vibrant, inclusive, and engaging urban environments that cater to the diverse needs and preferences of the urban population.

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GENERATING AND BREAKING THE RADIAL GRID FOR PROCEDURAL CITY LAYOUTS

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Abstract. This study investigates the generation and manipulation of radial grids for procedural city layouts, focusing on their potential for open-world games. Procedural city generation methods have gained prominence in various fields, including game development, architecture, and urban studies. This study introduces an organic city generation model utilizing procedural techniques, specifically adopting a radial grid approach as an alternative to rectangular grids. The paper presents three distinct mesh deformation techniques for altering the radial grid: One Point Attractor (OPA), Multiple Points Attractor (MPA), and Topography Informed Deformation (TID). These techniques are experimentally explored and empirically compared to achieve unique and heterogeneous growth patterns. As a result, the study develops modeling techniques for procedural city modeling based on radial grids that enable organic city generation and can be used in an open world game environment.

Keywords: *Procedural city generation, radial grid, radial growth, road network, open-world games.*

ملخص. تبحث هذه الدراسة في إنشاء الشبكات الشعاعية ومعالجتها لإنشاء تخطيطات للمدن بالنهج الإجرائى، مع التركيز على إمكاناتها في ألعاب العالم المفتوح. اكتسبت الأساليب الإجرائية لإنشاء المدن أهمية كبيرة في مجالات مختلفة، بما في ذلك تطوير الألعاب والعمارة والدراسات الحضرية. تقدم هذه الدراسة نموذج إنشاء مدينة عضوي باستخدام التقنيات الإجرائية، وعلى وجه التحديد اعتماد نهج الشبكة الشعاعية كبديل للشبكات

المستطيلة. تعرض الورقة ثلاث تقنيات مختلفة لتشوه الشبكة لتغيير الشبكة الشعاعية: جاذب ذو نقطة واحدة، جاذب متعدد النقاط، والتشوه المبنى على الطبوغرافيا. يتم استكشاف هذه التقنيات تجريبيًا ومقارنتها تجريبيًا لتحقيق أنماط نمو فريدة وغير متجانسة. ونتيجة لذلك، تقوم الدراسة بتطوير تقنيات النمذجة لنمذجة المدينة الإجرائية بناءً على الشبكات الشعاعية التي تتيح إنشاء مدينة عضوية ويمكن استخدامها في بيئة ألعاب عالمية مفتوحة.

الكلمات المفتاحية: *النهج الإجرائى لإنشاء وتوليد المدن، الشبكة الشعاعية، النمو الشعاعى، شبكات الطرق، ألعاب العالم المفتوح.*

1. Introduction

Deconstructing and depicting growth mechanisms have been applied not just to analyze the progression of living organisms but also to diverse computational frameworks and the formulation of urban development simulations. Thompson (1917) conducted a comprehensive investigation that would subsequently gain prominence within computational models. Thompson's (1917) key achievement in his “On Growth and Form” book lies in his capacity to elucidate common geometric principles underlying growth (Figure 1) processes across various scales (such as individual cells, tissues, organisms, etc.) and diverse processes (including biological, chemical, and physical aspects). Different from earlier equation-based analytic models, computational models offer executability, simulation capabilities, the ability to restart simulations with modified variables and parameters, the opportunity to observe the effects of parameter changes, and the visualization of intricate outcomes resulting from bottom-up processes (Kumar & Bentley, 2003).

Growth algorithms serve as computational design methodologies employed to simulate the processes of growth and development across diverse disciplines including architecture, biology, and urban and regional planning. In particular urban growth models, contingent upon technological advancements in the architectural domain, yield intricate and lifelike spatial designs. Among the prevalent techniques for generating organic urban textures, procedural urban production models stand out. These models have arisen as an efficient alternative to labor-intensive and time-consuming traditional modeling approaches. When applied to urban development models, the procedural city production method operates as an automated modeling approach, utilizing predefined parameters, algorithms, and rules based on sample cities. This method empowers users with a malleable design approach, allowing for easy customization and modification—a pivotal factor in crafting authentic urban landscapes within development models.

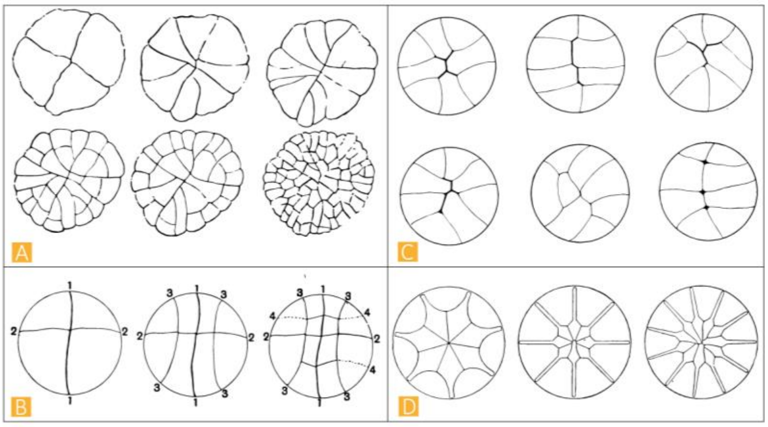


Figure 1. (a) Development of Erythrotrichia, (b) Segmentation of frog's egg, (c) Eight cells at pole of the frog's egg, (d) Diatoms of the Astrelampra marylandica. (Thompson, 1917: 359, 363, 381, 386).

Procedural models for urban pattern generation find prominent applications in video game development, filmmaking, urban design, and simulation models. They excel in rapidly generating intricate, highly detailed, and complex large-scale urban environments. This study aims to present an organic city generation model for gaming environments. It employs procedural city generation techniques, adopting a radial grid approach as an alternative to the commonly used rectangular grid. The resulting city model delves into the generation and alteration of the radial grid based on defined rules using three mesh deformation techniques.

2. Procedural Approaches in City Generation

Procedural techniques, which enable the creation of complex natural textures, special effects, and complex models such as trees, waterfalls, and urban designs, have become crucial techniques for modeling in computer environments with the development of computer technologies. This technique identifies geometry and textures suitable for creating urban spaces, especially for game environments, using a sequence creation instruction instead of static data blocks (Kelly & McGabe, 2006). Procedural modeling offers a flexible and manipulating user experience and production environment that can produce a wide variety of productions with minimal or no user intervention, especially by separating from traditional content creation methods (Sharma, 2016). When we look at the methods actively used in procedural modeling studies, we come across fractals, L-Systems, Perlin Noise, tiling, and Voronoi diagrams. Ebert et al. (2003) discussed procedural techniques under three main features: “abstraction” feature that integrates geometry and texture data into procedures that can be easily manipulated in the computer environment and calls these procedures when necessary, “parametric control” feature that enables developers to define and adjust parameters that govern certain procedural behaviors, enabling effective results without strict real-world boundaries, and “flexibility” feature, which allows the essence of an entity to be captured, enabling the production of various results beyond the limits of the original model. In this study, studies on procedural techniques were handled and examined under design & architecture, urban studies, and game industry titles.

2.1. DESIGN & ARCHITECTURAL CONTEXT

Procedural modeling is a generative technique used in a wide variety of applications such as plant generation, fractal noise and terrain generation, urban modeling, texture modeling, building, road network, and art creation (Ghorbania & Shariatpour, 2019; Vanegas et al., 2012a). One of the first features of procedural modeling, the L-system, was described by Lindenmayer (1968) as a set of generative rules for creating geometric structures. Later on, procedural modeling continues to grow in popularity in computer graphics in the fields of texture synthesis (Dylla et al., 2010; Ebert et al., 2003), noise generation (Dylla et al., 2010), and fractals (Luan et al., 2008; Ghorbania & Shariatpour, 2019). This use of computer visualization is also reflected in digital modeling, one of the architectural design tools. Due to simple parameters, interfaces, and rapid design generation, the procedural generation of buildings has become widespread in architectural auto-modeling (Yong et al., 2012). One of the first reflections in architecture is the form grammar method introduced by Stiny and Gips to analyze architectural design (Stiny & Gips, 1971). Parish and Müller (2001) proposed a procedural system for modeling city maps, geographical features, and buildings using L-systems. Müller and Wonka developed Computer-generated Architecture (CGA), an architectural procedural modeling grammar that produces high-quality, low-cost models (Müller et al., 2006). Edelsbrunner et al. (2017) propose a procedural technique to set up different coordinate systems in shape grammars to generate circular building geometry. Procedural techniques are used not only for the rapid output of the design process but also in architectural design in the fields of façade and architectural heritage. For example, several procedural techniques have been described to enable historical building processes from ancient Rome to modern Hong Kong (Birch et al., 2001); a procedural modeling system has been developed that allows users to change parameters to create buildings in the style of ancient East Asian architecture (Teoh, 2009). Recent studies have added tools such as shape grammar-based procedural modeling and augmented reality (AlFadalat & Al-Azhari, 2022). Examples of procedural techniques in another field of architecture are the works that propose a new procedural modeling framework for building 3D models of Chinese architectures concerning facade drawings (Hou et al., 2011) and procedural modeling for automatic derivation of shape grammar rules from facade images (Müller et al., 2007).

2.2. URBAN STUDIES

Urban modeling is another significant utilisation of procedural approaches. New procedural models have been developed for automatically modeling street layouts (Muller et al., 2006) and city blocks (Smith, 1984). One of the reasons for the application of procedural modeling in urban studies is that it summarizes complex relationships and allows users to quickly create large, complex 3D city models without having to be aware of many parameters and details (Batty, 2007; Parish & Muller, 2001; Honda et al., 2004; Weber et al., 2009; Vanegas et al., 2010; Vanegas et al., 2012b). A prospective procedural process by Parish and Muller (2001) describes a process for creating cities that utilize systems. Later Parish and Muller (2001) proposed CityEngine, a system that uses a procedural approach based on L-systems to model cities (Figure 2).

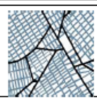
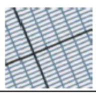
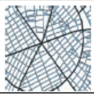
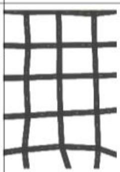
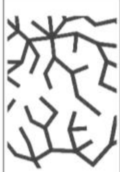
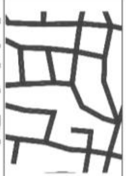
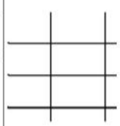
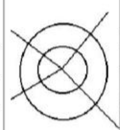
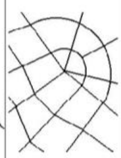
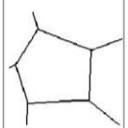
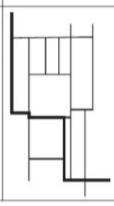
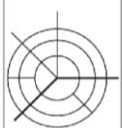
Pattern name	Pattern	Example
Basic	No superimposed pattern.	
New York	Rectangular Raster	
Paris	Radial to center	

Figure 2. Known cities in CityEngine application (Parish and Müller, 2001: 304).

Vanegas et al. (2010) and Watson et al. (2008) did follow-up work in prospective urban procedural modeling. Vanegas et al. (2012b) perform the interior partitioning of city blocks, i.e., partitioning by parcels, using user-defined subdivision attributes and style parameters. Another urban study proposes a procedure where users can create a street network from scratch or modify an existing street network by designing a tensor field (Chen et al., 2008). On the other hand, Frank and Ollson (2017) realized urban generations based on validity, determinism, performance, and flexibility parameters with Perlin noise. Sharma (2016) studied population-based procedural modeling in urban generation models. Most of the procedural city production models in the literature have created differentiated models using the grid types used by Sun et al. (2002). Table 1 shows the grid types used in three studies discussed in the literature.

TABLE 1. Models on procedural city generation in the literature.

	Type	Raster	Radial	Mixed	Organic	Industrial	Branching	Population based
References	Kelly & McCabe (2007)							
	Sun et al. (2002)							
	Parish & Müller (2001)							

2.3. GAME INDUSTRY

Urban models produced with procedural modeling techniques are nowadays widely observed in game development. The procedural modeling technique aims to algorithmically generate city-scale components such as roads, buildings, and landmarks to balance reality and creativity. This technique has become a flexible tool that can be shaped according to game dynamics, enhancing the player experience and allowing game developers to model complex urban formations quickly. Many games, such as Minecraft, use the procedural modeling technique. The procedural modeling technique is actively used in such games to create different urban environments quickly. In the literature, the Citygen procedural modeling tool proposed by Kelly and McCabe (2007) appears to allow the user to take an active role in the production process with an easily accessible and intuitive interface and manipulate the parameters considered in the production process. This study discusses procedural city generation under three headings: central road generation, secondary road generation, and building generation. Weber et al. (2009), while aiming to incorporate detailed urban geometry such as precise parcel boundaries, arbitrarily oriented streets, street widths, 3D street geometry, and building footprints into an urban simulation, introduced a new approach by incorporating time into this process under the decision to create a 4D city. Based on the changes that may occur over time, this approach offers the user the use of procedural techniques in growth algorithms at some point. Similar studies in the literature are based on certain components for cities created with procedural techniques. According to Erdei and Szénási (2023), these components are the Road system, City blocks closed by roads, Cut city blocks into building plots and side streets, and Filling up plots with city objects like buildings. The game environment based on these components and created with procedural modeling is a virtual reality environment, which is another digital environment that has become widespread today. Accordingly, there are examples where procedural modeling is used for virtual cities and city designs suitable for virtual reality environments (Gaisbauer & Hlavacs, 2017; Gaisbauer et al., 2020). As a result, procedural city generation methods are seen as a dynamic tool for building large and engaging virtual cities in game development. As technology advances and algorithms improve, procedural modeling methods will be used to create increasingly detailed and diverse urban spaces.

3. Methodology

This study adopts an experimental approach and employs empirical comparison of outcomes. The experiment setup consists of three main axes namely One Point Attractor (OPA), Multiple Points Attractor (MPA), and Topography Informed Deformation (TID). The aim of these experiments is to explore and attain non-symmetric, differentiated, heterogeneous growth patterns and techniques. A shared characteristic among these three techniques is the utilization of a specific geometry as a starting point, known as a radial grid (Figure 3). The basic steps are shown below:

1. Construction of initial radial grid (Center point, number of circles, number of folds, offset value);
2. Deformation function (distance-based attractor, user-defined function, etc.)
3. Comparison of the outcomes.

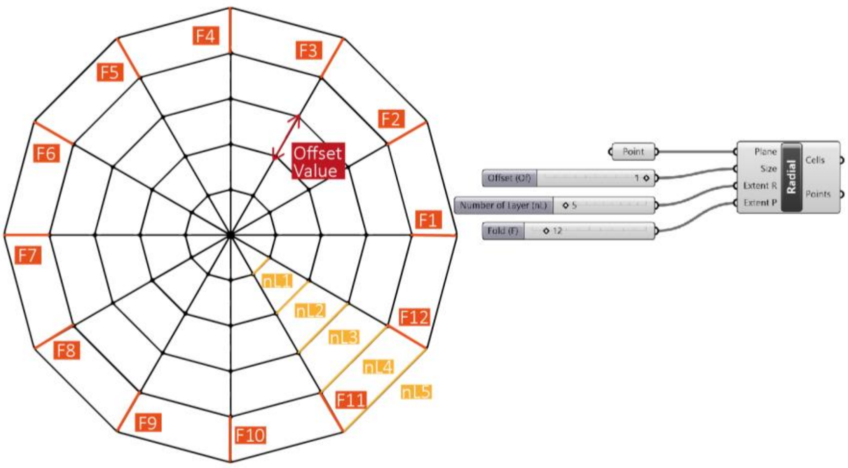


Figure 3. A sample of the definition of the radial grid in the Grasshopper environment.

The distinctions between the three radial grid deformation techniques are illustrated in Figure 4. While each technique commences with a designated radial grid, variations emerge in terms of input types and executed functions. In the OPA case, the process entails computing the distance between an attractor point and the vertices of the initial radial grid. MPA incorporates the calculation of distances among multiple points, in addition to the distance values between attractor points and the vertices of the initial radial grid. In TID, the source of data involves utilizing the slope value from a given or predefined 3D surface (Figure 4). The distance information can be interpreted in terms of direct proportionality, inverse proportionality, or by utilizing a user-defined mathematical function.

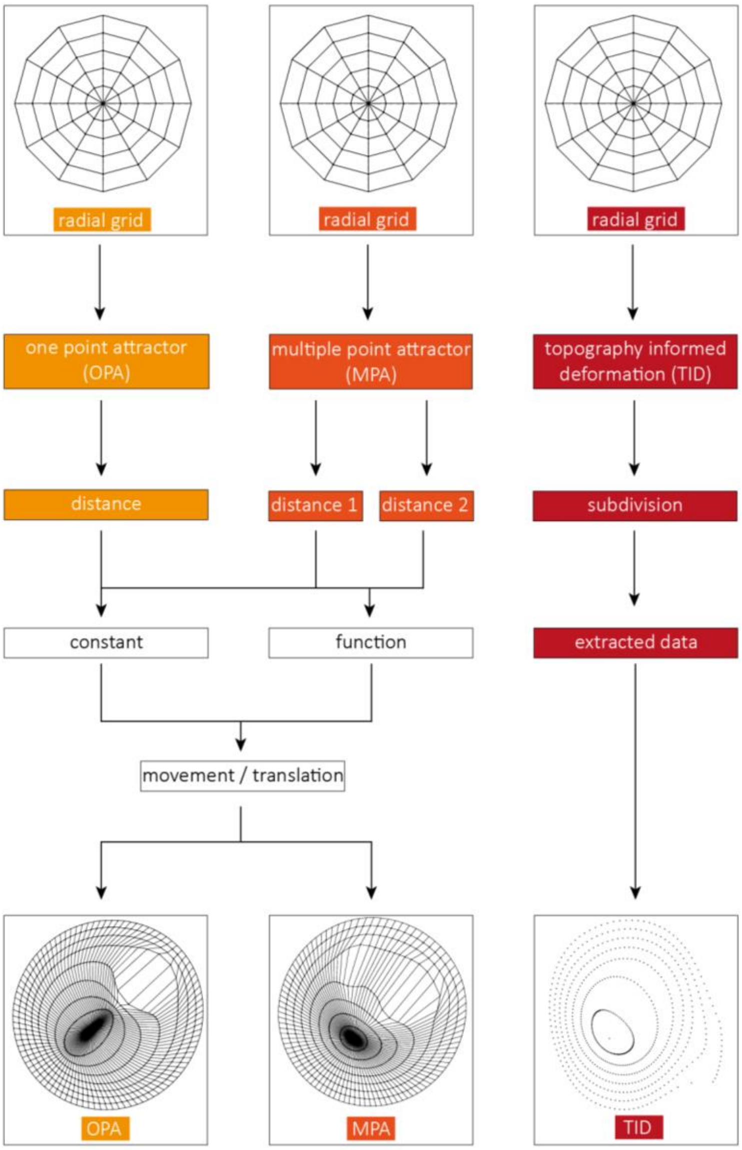


Figure 4. Algorithm schema of the three radial grid deformation techniques.

4. Implementation of Three Radial Growth Techniques

4.1. SCOPE AND LIMITATIONS

In the scope of this study, Rhinoceros 7.0 and Grasshopper environment is utilized as a 3D modeling tool. Given that the initial geometry is established through variable definitions, a diverse range of parameters and applied functions are subjected to testing.

4.2. ALGORITHMS

Deformation and differentiation of a given grid is not a new study. Ipek et al. (2012) investigated deformation of a given grid from a structural performance perspective. In their research, Ipek et al. (2012) explored the deformation of grids, including radial grids as an initial geometry, as well as hexagonal and orthogonal grids. In the context of One Point Attractor (OPA) applications, a key process involves the calculation of distance values between the attractor point and other points. Subsequently, an additional translation (move, rotate, scale) or transformation (modify, etc.) operation is carried out based on these distance values. Ipek et al.'s (2012) study introduces a significant contribution by incorporating the computation of the value 1/x^2 based on the calculated distance value. The OPA algorithm presented in this study adopts Ipek et al.'s (2012) mesh deformation approach. Additionally, in the Multiple Points Attractor (MPA) approach, calculations involve the interaction of values among attractor points, along with the consideration of distance values between the vertices of a given grid and the attractor points. Considering Topography Informed Deformation (TID), a given surface is associated with the initial radial grid through reflecting the grid points onto the surface by using “pull” command. Further to achieving points on surface, these points are used as inputs for the following operations including project or attractor point based translation. While, TID is inspired from Bacınoğlu et al. (2013), it distinguishes itself through variations in inputs and procedural steps. TID is shown in Figure 5.

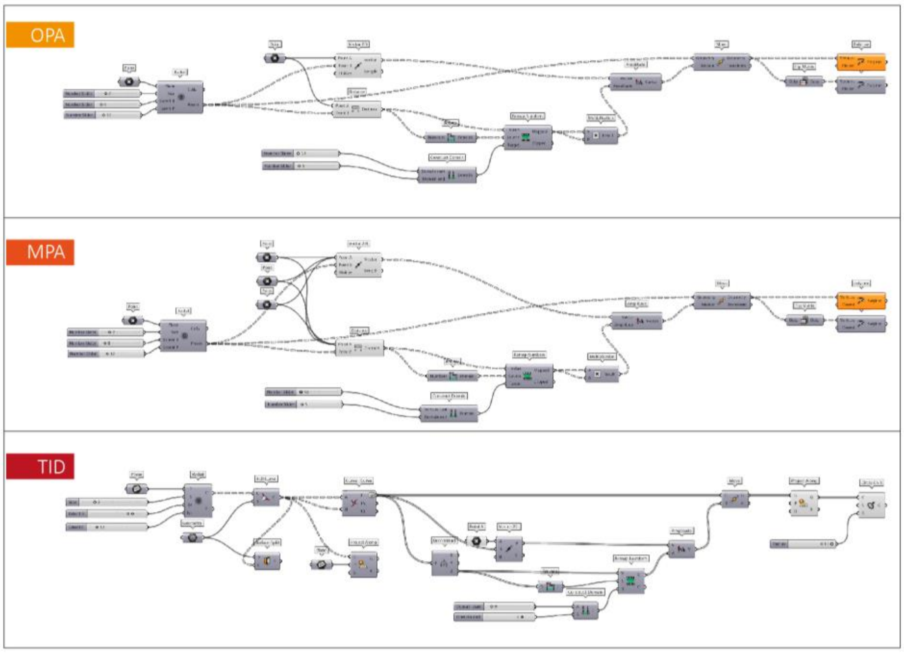


Figure 5. A Screenshot from Grasshopper illustrating basic components of OPA, MPA and TID respectively.

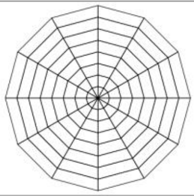
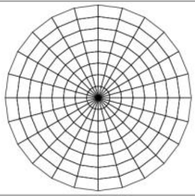
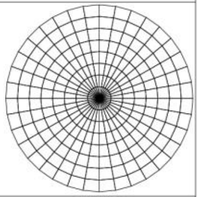
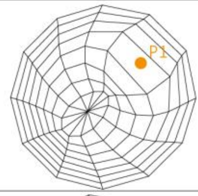
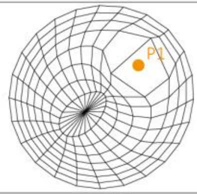
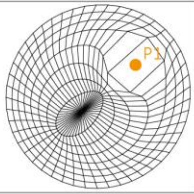
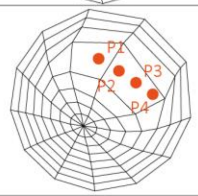
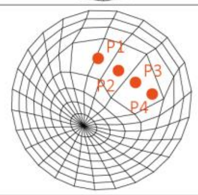
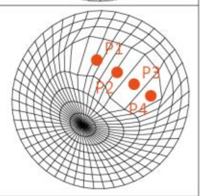
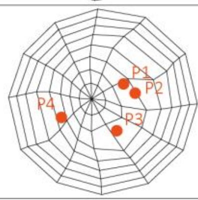
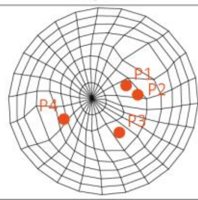
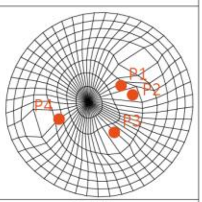
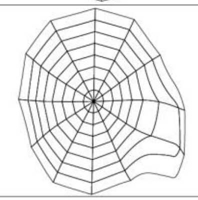
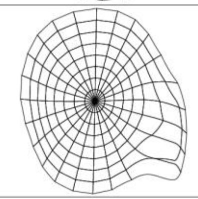
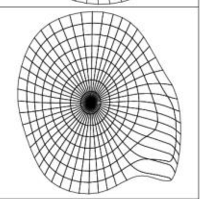
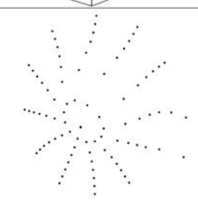
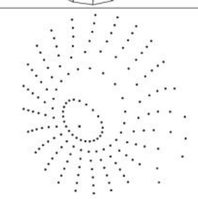
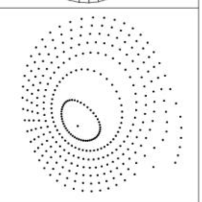
4.3. FINDING AND OUTCOMES

A set of outcomes regarding the implementation of the three radial grid deformation techniques are given in Table 2.

5. Conclusion and Discussion

In this study, we have delved into the generation and manipulation of radial grids for procedural city layouts, particularly focusing on their applicability within open-world games. We have introduced an organic city generation model that employs procedural techniques, with a specific emphasis on adopting a radial grid approach as an alternative to conventional rectangular grids. Our investigation encompasses three distinct mesh deformation techniques: One Point Attractor (OPA), Multiple Points Attractor (MPA), and Topography Informed Deformation (TID). Through experimental exploration and empirical comparisons, we sought to achieve heterogeneous growth patterns and techniques that deviate from symmetry.

TABLE 2. Outcomes of the three radial grid deformation techniques.

	12 Fold	24 Fold	48 Fold
Initial Grid offset: 2 number of layers:8			
OPA remap(min)= 3 remap(max)=5 f(x) = x^2;			
MPA remap(min)= 1.6 remap(max)=1.74 f(x) = x^2; 4 attractor points (sequential order)			
MPA remap(min)= 1.6 remap(max)=1.74 f(x) = x^2; 4 attractor points (complex order)			
TID pull > project			
TID pull >attractor			

In the city modeling procedures discussed in the literature (Kelly and McCabe, 2007; Sun et al., 2002; Parish and Müller, 2001), the initial grid is usually based on rectangular grids with homogeneous and regular characteristics. Depending on the initial grids and the procedures applied, this approach prevents the intended heterogeneous and organic patterns of city formation from emerging. This study proposes new techniques for city modeling and growth algorithms with the radial initial grid and the applied OPA, MPA and TID procedures.

In the execution of OPA and MPA, we employed the square of the distance value instead of utilizing the raw distance value itself. This execution was inspired from Ipek et al.'s (2012) study. The "x2" function can be extended in future research, as it introduces smooth and curved transitions in the resultant outcomes. This could encompass the utilization of complex numbers, equations of higher degrees, and the exploration of fractal formations. Another constraint of this study is the absence of an exploration into the mathematical growth patterns of the generated designs as they evolve similar to tiling patterns. Therefore, this study can be considered as an initial exploratory step towards developing an approach for procedurally generating radial patterns and a proof-of-concept study.

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A SYNERGY OF AI OBSERVATION AND DESIGN TOOL

Leveraging Multifaceted AI Techniques for Encoding Human Behaviours and Stories in Space

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Abstract. This paper presents an innovative AI-powered tool aimed at revolutionizing observational methods in architectural design. Its primary objective is to bridge the existing gap between designers and AI predictions, streamlining and enhancing the design process. The tool facilitates the creation of dynamic visualizations that predict human behaviours within 3D design models, adapting seamlessly to design alterations. This prototype showcases the potential for efficient AI-assisted design. The core of our system consists of an AI model that trains on data related to human behavior within environmental contexts. Our user-friendly interface empowers designers to interact dynamically with their 3D modelling tool, akin to playing an interactive chess game. Designers can populate their models with human characters, and the system, in turn, predicts the likely activities of these characters. Observational techniques are pivotal in architectural design, drawing inspiration from influential works such as those by Alexander and Whyte. They provide a comprehensive understanding of how spaces can foster human interaction and help architects, designers, and urban planners make informed decisions that enhance user-friendliness. Nevertheless, two key challenges hinder the effective utilization of this data. Firstly, there is a lack of an intuitive interface that seamlessly integrates with existing tools. Designers often struggle to translate the information into design parameters and interpret the data effectively. Secondly, architects must adapt to evolving living environments and cultural shifts, necessitating real-time observations. However, time constraints and biases impede this process. A solution allowing designers to easily update their data is imperative. Our system comprises three integral components: a pre-trained model adaptable to specific locations, depth prediction and segmentation models for spatial comprehension, and a recognition model for user-designed structures. These features, combined with a user-friendly interface, empower designers to interact intuitively with their models, facilitating more informed and responsive design decisions.

Keywords: *AI-powered tool, Observational methods, Spatial comprehension, Human behaviours, Dynamic visualizations, Camera Based-Analysis.*

ملخص. تقدم هذه الورقة أداة مبتكرة تعمل بالذكاء الاصطناعي تهدف إلى إحداث ثورة في مناهج المشاهدة في التصميم المعماري. هدفها الأساسي هو سد الفجوة القائمة بين المصممين وتوقعات الذكاء الاصطناعي، وتبسيط وتعزيز عملية التصميم. تسهل الأداة إنشاء تصورات ديناميكية تتنبأ بالسلوكيات البشرية ضمن نماذج التصميم ثلاثية الأبعاد، وتتكيف بسلاسة مع تعديلات التصميم. يعرض هذا النموذج الأولي إمكانية التصميم الفعال بمساعدة الذكاء الاصطناعي. يتكون جوهر نظامنا من نموذج الذكاء الاصطناعي الذي يتدرب على البيانات المتعلقة بالسلوك البشري ضمن السياقات البيئية. تعمل واجهتنا سهلة الاستخدام على تمكين المصممين من التفاعل ديناميكيًا مع أداة النمذجة ثلاثية الأبعاد الخاصة بهم، تمامًا مثل لعب لعبة شطرنج تفاعلية. يستطيع المصممون ملء نماذجهم بشخصيات بشرية، ويقوم النظام بدوره بالتنبؤ بالأنشطة المحتملة لهذه الشخصيات. تعتبر تقنيات المراقبة محورية في التصميم المعماري، فهي مستوحاة من الأعمال المؤثرة مثل أعمال ألكساندر ووايت. إنها توفر فهمًا شاملاً لكيفية تعزيز المساحات للتفاعل البشري ومساعدة المهندسين المعماريين والمصممين والمخططين الحضريين على اتخاذ قرارات مستنيرة تعزز سهولة الاستخدام. ومع ذلك، هناك تحديان رئيسيان يعيقان الاستخدام الفعال لهذه البيانات. أولاً، هناك نقص في الواجهة البديهية التي تتكامل بسلاسة مع الأدوات الموجودة. غالبًا ما يواجه المصممون صعوبة في ترجمة المعلومات إلى معلمات التصميم وتفسير البيانات بشكل فعال. ثانيا، يجب على المهندسين المعماريين التكيف مع البيئات المعيشية المتطورة والتحولات الثقافية، مما يستلزم الملاحظات في الوقت الحقيقي. إلا أن ضيق الوقت والتحيزات تعيق هذه العملية. يعد الحل الذي يسمح للمصممين بتحديث بياناتهم بسهولة أمرًا ضروريًا. يتكون نظامنا من ثلاثة مكونات متكاملة: نموذج مُدرب مسبقًا وقابل للتكيف مع مواقع محددة، ونماذج التنبؤ بالعمق والتجزئة للفهم المكاني، ونموذج التعرف على الهياكل التي صممها المستخدم. تعمل هذه الميزات، جنبًا إلى جنب مع واجهة سهلة الاستخدام، على تمكين المصممين من التفاعل بشكل حدسي مع نماذجهم، مما يسهل اتخاذ قرارات تصميمية أكثر استنارة واستجابة.

الكلمات المفتاحية: *أداة تعمل بالذكاء الاصطناعى، مناهج المشاهدة، الفهم الفراغى، السلوك الإنسانى، الرؤى الديناميكية، التحليل باستخدام الكاميرات.*

1. Introduction and Overview

In the modern field of architecture, the creation of physical spaces is more than just the assembly of structures; it serves as a reflection and influence on society, culture, and individual perspectives (Borah, 2021). Contemporary architects prioritize community engagement and social consciousness in their designs, creating spaces that not only accommodate societal needs but also address important issues such as sustainability and disaster relief. The goal is to foster a sense of belonging and address modern social challenges. In this context, understanding human behavior and social dynamics in open spaces becomes crucial. Videos and photographs, now more accessible than ever through online and social media platforms, have emerged as invaluable resources for capturing these complex interactions. By analyzing this data, architects can gain insights into how people interact with their surroundings, which in turn informs designs that promote community engagement and social well-being.

In this context, we have developed a real-time analytical tool capable of predicting human behavior within the context of 3D modeling. This tool examines 3D models created within specific design software and evaluates how well the spatial design aligns with its intended purpose or program. This tool's heart is a network trained on a dataset carefully cultivated through a nuanced multi-model approach. This approach skillfully isolates key high-level features by parsing both videos and their accompanying captions using a range of pre-established models. Focusing on these essential features reduces the number of training features, which enhances the network's accuracy in predicting human behavior within different spatial contexts.

Moreover, this tool has been designed with adaptability in mind. It can be fine-tuned or retrained to align with different locales and situations. Recognizing the multifaceted nature of human behavior—shaped by cultural, environmental, and temporal determinants—this tool's adaptability ensures its relevance and effectiveness across diverse architectural design challenges.

The practical implications of this tool are far-reaching. For architects and urban planners, it can serve as a valuable assistant in creating spaces better tailored to their users' needs and behaviors. By providing insights into how people are likely to interact with a given space, designers can make more informed decisions in their design processes. This can lead to more functional and enjoyable spaces, contributing to improved quality of life for those who use them.

In addition to its applications in architectural design and urban planning, this tool holds potential for use in sociological research. Researchers can gain deeper insights into social dynamics and the factors affecting them by analyzing human behavior in various spatial contexts. This knowledge can inform policies and initiatives to foster positive social interactions and create more inclusive and harmonious communities.

2. Introduction

In the modern field of architecture, the creation of physical spaces is more than just the assembly of structures; it serves as a reflection and influence on society, culture, and individual perspectives (Borah, 2021). Contemporary architects prioritize community engagement and social consciousness in their designs, creating spaces that not only accommodate societal needs but also address important issues such as sustainability and disaster relief. The goal is to foster a sense of belonging and address modern social challenges. In this context, understanding human behavior and social dynamics in open spaces becomes crucial. Most related research and projects are inspired by the principles outlined in Christopher Alexander's seminal work, "A Pattern Language," which investigates how architectural and urban design patterns can be used to create more harmonious and liveable spaces (Alexander, 1977). In parallel, the influential research of William H. Whyte, "The Social Life of Small Urban Spaces," holds significant value within urban planning, design, and architecture (Whyte, 1980). Whyte's work explores how people interact with and utilize public spaces, offering critical insights into the complex relationship between spatial design, human behaviour, and social dynamics.

In an era characterized by the proliferation of videos and photos, easily accessible through online and social media platforms, architects have come to recognize the invaluable potential of these resources for capturing intricate interactions and enriching the design process with valuable data. However, the seamless integration of data tools into architectural design firms faces significant challenges. Firstly, there is a pressing need for efficient techniques to organize and make sense of vast and unfamiliar datasets, thereby enhancing their practical utility. Secondly, there is a scarcity of data experts within these firms who possess the expertise to effectively manage various data sources and tools tailored to meet specific project requirements (Deutsch, 2015). While some approaches have been proposed to address these challenges, the recent emergence of AI has ushered in a revolution in the field of design, offering powerful tools to address complex problems and augment creativity (Cheng, 2017). As a result, a range of AI-related methods has started to gain prominence in addressing these needs.

MIT City Science Group studies urban areas' social, economic, and physical aspects to improve urban design practices and promote agreement among stakeholders. They introduce CityScope (2018), a data-driven platform that

simulates how urban changes affect ecosystems, allowing stakeholders to collectively assess and optimize interventions in real time. In this article, they outline the methodology of the tool, offering an innovative approach to urban design strategies.
In 2022, the SWA Group conducted the "Plaza Life Revisited" project, with the aim of examining the evolution of contemporary public spaces, revisiting them four decades after the publication of its associated book and film. The project's primary objective was to analyse shifts in how people utilize public realm spaces and identify the elements contributing to the success of these spaces. Initially, the study focused on ten plazas in Manhattan, each designed by different architects and either constructed or renovated within the past 15 years. To gain insights, the project utilized computer vision and AI algorithms to generate valuable data, including heat maps depicting dwell times, patterns of frequent and infrequent usage, as well as preliminary pedestrian counts.
In summary, the projects mentioned above have advanced data-driven design in the field of architecture, providing valuable insights. However, these approaches are currently too complex and costly for designers to readily adopt. For instance, while the visualizations are comprehensive and insightful, there exists a gap between these mediums and the design tools used by architects. Furthermore, designers may be unsure about updating or customizing the simulator and data to align with specific project requirements. This paper aims to address these challenges by developing a streamlined process to bridge this gap and make data-driven design more accessible for architects.

3. Multifaceted AI Techniques

We present an innovative tool that harnesses the power of AI to predict and analyse potential behaviors and social interactions within a designated architectural space. This cutting-edge tool seamlessly integrates with popular 3D modelling platforms like Rhino Grasshopper and Python, allowing users to interactively tag tokens representing potential human activities. As users position agents within their 3D designs, this tool provides valuable insights into the expected behaviours within the space.
Architects and designers can now engage in a dynamic, iterative design process that considers the implications of human behavior at every stage. By offering immediate feedback on how modifications to the architectural space might impact human activities and interactions, our tool empowers professionals to optimize their designs for the intended users and purposes.
At the core of this tool lies a sophisticated Multifaceted AI approach, which combines a range of machine learning models and algorithms to thoroughly analyze and predict human behavior within 3D environments. This multi-model system draws from diverse data sources, including video captions,

images, and user-generated tags, to extract essential features and patterns associated with human behaviour across various spatial contexts.
The predictive capabilities of our tool are further enriched through a combination of supervised and unsupervised learning methods. Supervised learning enables the tool to refine its predictions based on labelled examples and historical data, while unsupervised learning uncovers hidden patterns and relationships within the data, revealing novel insights into potential human behaviours that may have previously gone unnoticed.
This comprehensive system (see Figure1) offers architects and designers a nuanced understanding of human behaviour within architectural spaces, enabling them to make well-informed decisions throughout the design process. By leveraging real-time feedback and insights from the tool, designers can create spaces that not only meet aesthetic and functional requirements but also facilitate positive social interactions, ultimately enhancing the overall user experience.

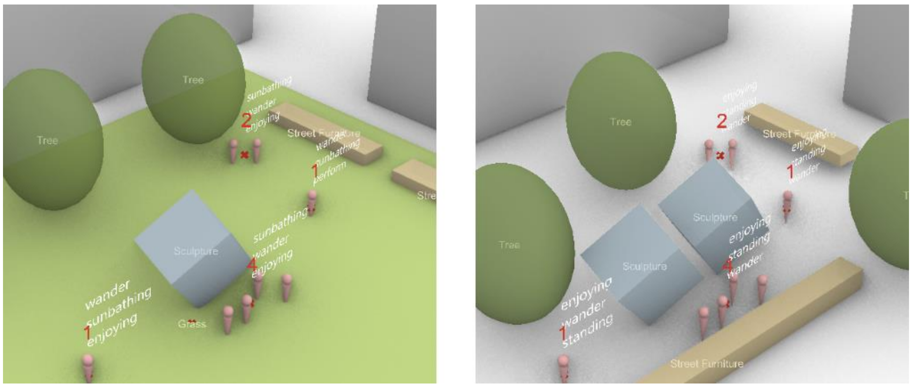

Figure 1. Dynamic Visualization of people's behavior in a design model.

Illustratively, subsequent figures depict two distinct designs eliciting varied predictions. To augment the user experience, the tool is equipped with an automatic object recognition system, bypassing the need for manual categorization of objects during estimations. This fluidity ensures that users can direct their focus on design intricacies, while simultaneously gaining insights and prompts from the estimation interface.
The underlying estimation algorithm gleans its training from genuine video footage showcasing human dynamics in open urban settings, underscoring its authenticity and applicability. Through invaluable feedback from preliminary user interactions, the tool's performance and usability have been honed.
Furthermore, the system boasts intrinsic adaptability. It can be seamlessly retrained and adjusted, providing an avenue to mold the tool's predictions to

fit varied contexts and environments. Such versatility ensures that users can align the tool's output to distinct design challenges and requirements.

4. System for Behavior Forecasting

The present system seeks to understand and predict human behavior within a given architectural space by analyzing 3D models. This system comprises two main components, as depicted in Figure 2. In the first component, our system employs a multi-model approach to extract essential and high-level information from images and captions extracted from videos. This information encompasses spatial characteristics and the behavior of individuals in the space, including their movements, interactions, and activities. By aggregating this information, the system forms a comprehensive dataset representing a wide array of architectural spaces and the behaviors of people within them. This dataset then serves as a foundation for training predictive models.

The second component of our system involves training a straightforward neural network using the dataset created in the first component. This neural network estimates and predicts people's behavior within a 3D modeling environment, as shown in Figure 3. In this 3D modeling environment, architects and designers can create virtual representations of their designs and simulate people's likely interactions with them. The neural network provides insights into how people will move through space, where they may gather, and how they will interact with their surroundings.

The system offers valuable insights into how people behave in various architectural spaces by employing both components. These insights equip architects and designers to make more informed decisions when creating their designs and to optimize spaces to meet the needs and preferences of users. Additionally, the system's adaptability allows for its application across various architectural projects, ranging from small-scale residential designs to large-scale commercial spaces. It can accommodate different types of data inputs, including images, videos, and text-based descriptions of spaces, further increasing its versatility. This adaptability establishes the system as an invaluable tool for architects and designers to create spaces that better respond to user needs.

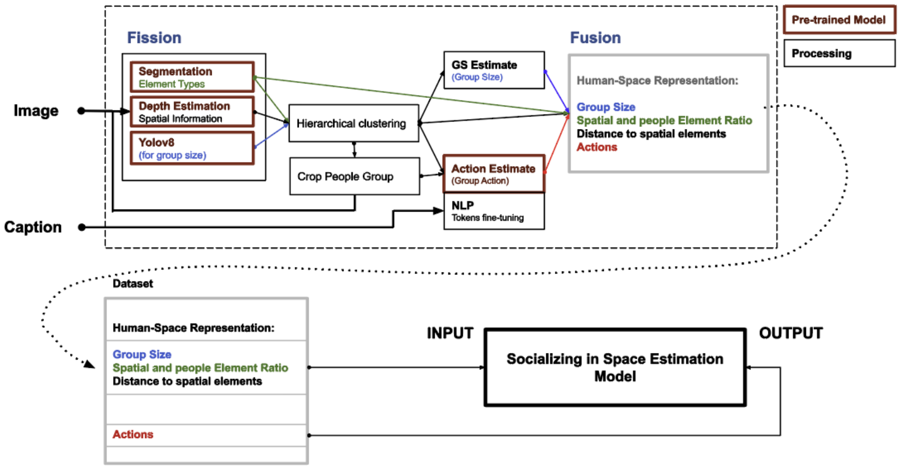

Figure 2. The system flowchart.

A multi-model technique is adopted to extract pivotal and high-tier data from images and video captions, culminating in a rich dataset.
A neural network is subsequently trained, which is geared towards estimating human behavior in a 3D modeling context (see Figure 3).

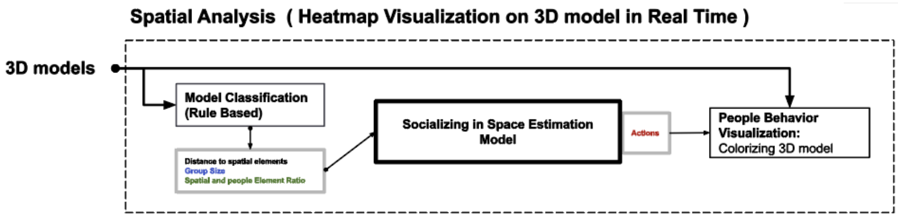

Figure 3. Spatial Analysis.

For a comprehensive analysis, the system integrates depth estimation to reproduce a 3D scene from 2D images, essential for deducing behavior in a three-dimensional setup. This is coupled with a semantic segmentation model that discerns and categorizes elements within the scene – from individuals to architectural entities like buildings and street features. This dual-model approach uncovers relationships between human behaviors and their environmental contexts. As a result, a 3D point cloud emerges, with each point assigned a distinct label. To ensure this data is cohesively organized, a hierarchical clustering technique is deployed.

Post-clustering, the system utilizes an action estimation model (based on 'Moments in Time') to deduce individual group actions (Monfort et al., 2018). Bounding boxes, marking clustered individuals, guide the system to specific image regions for precise analysis (refer to Figure 4). Additionally, the YOLO (You Only Look Once) object detection algorithm quantifies individuals within these focused image sections, determining group magnitude (Redmon et al., 2016).

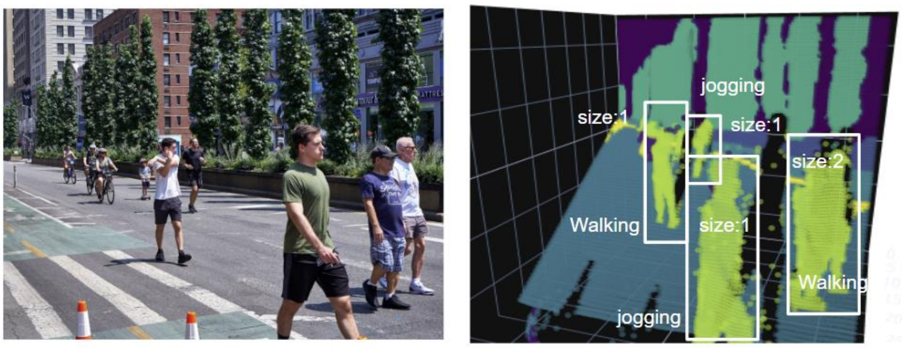

Figure 4. Bounding boxes marking clustered individuals.

We employed a combination of techniques to improve the correlation between predicted tokens and original video captions. First, we utilized T-SNE for dimensionality reduction, a technique that simplifies complex data structures without sacrificing the relationships between data points. Second, we adopted the GloVe 100D model for word embeddings, which allows us to convert words into numerical vectors that reflect their contextual meanings. Together, these methods assist us in identifying the most closely aligned token from a video's transcription, which then informs action predictions. We facilitated the transcriptions using the Google Speech-to-Text API.

After completing these procedures, our system evaluates correlations between groups and spatial elements. It does this by measuring proximities through the central points of grouped entities. As an example, if the system identifies a group engaging in a picnic near a tree, it learns that people tend to picnic close to trees. This observation contributes to the system's knowledge of inherent behaviors associated with specific spatial elements.

Our human-centric dataset for this project, depicted in Figure 5, encompasses the environmental context surrounding groups. It details their actions, group sizes, and the scene's composition in terms of element percentages. We acknowledge that behaviors are influenced by variables such as group size and environmental components. Therefore, to ensure the model's foundational strength for accurate behavior assessments, we curated a dataset of 1,000 data points. This extensive dataset captures various

behaviors and spatial contexts, making it an invaluable resource for training our predictive model.
Our system can uncover patterns and relationships between behaviors and spatial elements by analyzing the dataset (see Figure 5). This deeper understanding allows our system to make more informed predictions, aiding architects and designers in creating spaces better suited to human behavior. We intend to refine our model by incorporating additional data and implementing more advanced machine-learning techniques as we move forward. Ultimately, our goal is to provide a powerful tool that enhances the design process and helps create spaces more responsive to their users' needs and preferences.

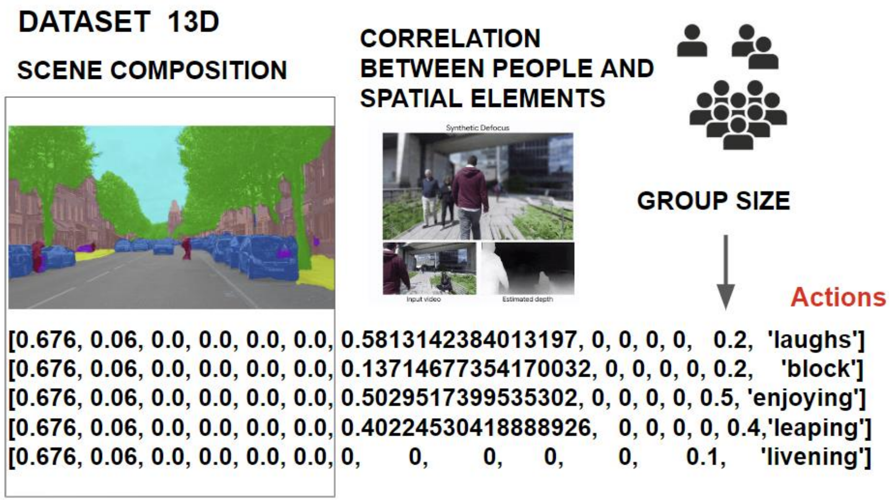

Figure 5. The dataset format

5. Implementation

We selected a video from William H. Whyte's influential documentary, "The Social Life of Small Urban Spaces" (1980). We used this documentary as a foundational reference to understand human behavior and interactions within open spaces. In this documentary, Whyte meticulously investigates the dynamics of urban public spaces, examining how people navigate and utilize areas like plazas, parks, and sidewalks. His thorough research reveals factors contributing to a space's success or failure, including its design, layout, seating arrangements, and overall ambiance. We chose this documentary for its well-organized content focusing on people's behavior in open spaces. Moreover, the captions of the documentary provide abundant information, enabling us to employ string-processing techniques to extract relevant clips easily.

Our system gains essential knowledge about common social behaviors and patterns in urban settings. We must note that the low resolution of the documentary presented a challenge. Nonetheless, we successfully addressed this issue, showcasing our system's potential applicability to a wide variety of video sources. To break down and analyze the documentary, we used the Google speech-to-text API to convert video content into images and tokens suitable for analysis.

We then fine-tuned the model using our human-centric dataset and integrated it into Rhino Grasshopper, a powerful visual programming language equipped with a graphical algorithm editor. Grasshopper allows users to explore parametric and generative design, enabling them to create intricate shapes and patterns by interconnecting numerous components and parameters. Within this environment, users can intuitively tag tokens to represent potential activities of figures in the 3D models. As a result, our tool offers dynamic behavior predictions that update in real-time as users modify the 3D designs.

To train the neural network, we utilized the machine-learning library, Lunchbox, within Grasshopper. Lunchbox streamlines (refer to Figure 6) the training process with the provided dataset. Upon completing the training, we saved the resultant weights as a file so the Lunchbox library could access them during the estimation phase. This integration with Grasshopper enables a seamless transition from training to estimation, and users can immediately see the effects of their design modifications on human behavior predictions. This feature empowers architects and urban planners to test various design ideas and assess their impact on human interactions, helping them create spaces that encourage desired behaviors and improve overall user experiences.

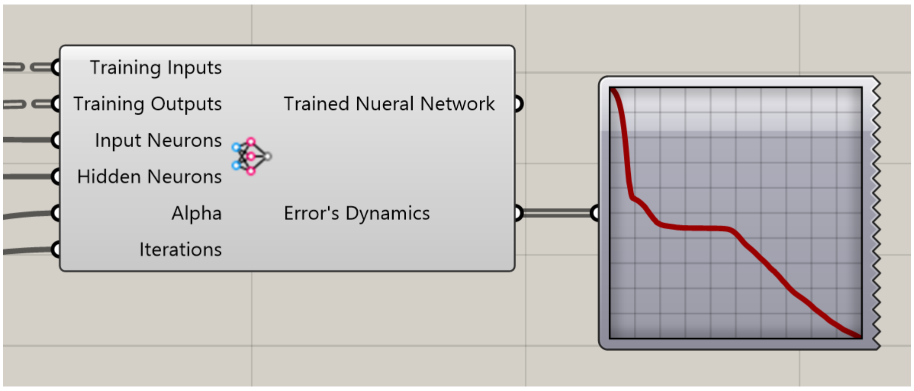

Figure 6. The Lunchbox Neural Network Component.

Ingredients of the tool development

The following provides an overview of the various libraries, tools, and packages utilized for the system, along with their specific usages and the types of input data they handle.

Library/Package/Tool:

PyTorch: This library is used for depth estimation, semantic segmentation, and activity estimation within the project. It is a popular deep learning framework that allows for flexible model creation and training.

PIL (Python Imaging Library): This library is employed for generating the dataset. It is widely used for opening, manipulating, and saving image files.

OpenCV Version 2: This library is essential for computer vision tasks, though its specific usage is not mentioned in the table.

Scikit-Learn: This machine learning library is used for fine-tuning token output along with the NLTK. It offers a wide range of tools for data mining and data analysis.

NLTK (Natural Language Toolkit): This library, used in conjunction with Scikit-Learn, is employed for fine-tuning token output. It is a leading platform for building Python programs to work with human language data.

GloVe (Global Vectors for Word Representation): While the specific usage is not mentioned in the table, GloVe is typically used for word embeddings, which can be instrumental in natural language processing tasks.

Grasshopper (in Rhino 3D): This 3D modeling platform is used to implement the network in the existing 3D modeling tool. It allows for algorithmic modeling for Rhino.

Lunchbox (Machine Learning library in Rhino 3D): This library, used in conjunction with Rhino and Grasshopper, helps implement the network in the existing 3D modeling tool.

Usages:

Pytorch: Depth Estimation, Semantic Segmentation, Activity Estimation
PIL: Generating Dataset

Scikit-Learn, and NLTK: Fine-tuning token output
Rhino, Grasshopper, and Lunchbox: Implement Network in Existing 3D Modeling Tool
Data Types of the Input:

mp4: Video files used as input for analysis.
txt: Text files, potentially used for annotations or transcriptions.
3D model in Rhino: 3D models created in Rhino that are used for spatial design and behavior prediction.

6. Conclusion

This paper has unveiled an innovative AI-powered tool with the transformative potential to reshape observational techniques in architectural design. At its core, the tool's objective is to reconcile the perceived gap between the organic design intuition of architects and the precision of AI predictions. The main advantage lies in its capacity to generate dynamic visualizations that forecast human behaviors in 3D spaces. Adjustments to designs are fluidly accommodated, allowing for immediate visualization of resultant human behavioural patterns. This tool's introduction embodies the evolution of AI-assisted design, where technology doesn't merely optimize, but also nurtures the creative essence of design, leading to spaces that resonate harmoniously with human interaction.

7. Discussion

Historically, the design process, as described by Mitchell (1990), has embraced the trial-and-error approach as intrinsic to creativity. Mirroring this philosophy, our tool grants designers the liberty to tweak designs while simultaneously observing emergent human behaviour. This real-time feedback loop promotes an integrated approach, marrying human-centric requirements with geometric considerations. Such computational aids, supported by Stiny's observation from 2001, provide a fresh vantage point, challenging designers to perceive their work differently. With this tool, designers gain deeper insights into the intricate dance between spatial designs and human behaviours. Building upon this, our methodology adopts a comprehensive strategy for deciphering human behaviour in architectural contexts. Beginning with a rich dataset representing diverse architectural spaces and associated human behaviours, we employ a gamut of data collection techniques. Post-collection, rigorous preprocessing gleans features that depict the nuanced relationship between spatial design and human dynamics. This foundational dataset serves as the bedrock for training our predictive model, ensuring it captures the myriad ways individuals engage with architectural spaces. The distinguishing feature of our approach is the symbiotic relationship between the predictive model and the 3D modelling platform. This integration is instrumental in simulating human behaviour within projected designs, offering invaluable foresight into potential design inefficiencies or crowding hotspots.

8. Future works

While the prototype is promising, we acknowledge its static nature. It provides insights tethered to specific design alterations, potentially overlooking the fluidity of human behavior. As an advancement, we propose the integration of agent-based modeling, simulating the behavior of individual agents, each operating with unique goals. This nuanced understanding will offer more accurate projections of human interactions within architectural designs. Another avenue worth exploring is the utilization of attention-based models. Recognized for their prowess in parsing sequential data, these models could provide temporal trajectories of human behaviors, shedding light on their movement patterns and adaptations over time. Lastly, recognizing that our interface is still in its nascent stage, further enhancements are slated. Post usability testing and feedback integration, our end goal remains to furnish architects and designers with an intuitive, efficient tool to sculpt spaces that are not only aesthetically pleasing but also optimized for human inhabitation.

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3.B.

DIGITAL HERITAGE AND CULTURE - II

EXPLORING THE INTEGRATION OF MID-JOURNEY AI FOR ARCHITECTURAL POST-OCCUPANCY EVALUATION: PRIORITIZING EXPERIENTIAL ASSESSMENT

Case Study of the Egyptian Museum (EM) & National Museum of Egyptian Civilization (NMEC)

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Abstract. The post-occupancy evaluation (POE) process, traditionally reliant on subjective user feedback and observations, has evolved in response to global concerns like climate change and sustainability. This shift towards greater objectivity and quantification reflects an increased focus on precise measurement of environmental and performance metrics. Consequently, architectural assessment is now more quantitatively oriented, moving away from a predominantly experiential emphasis. This research investigates the integration of the emerging AI tool Mid-journey into the POE process, specifically targeting the evaluation of experiential aspects in architectural design. It proposes that AI tools can be instrumental for architects and evaluators by translating user feedback into visual representations and conceptual insights. The study aims to initiate a discourse on the role of text-to-image models in assessing user experiences, potentially becoming integral to the design and concept generation process. The research combines quantitative methods like surveys and AI-driven experiments with qualitative approaches such as observations and interviews to offer enhancement proposals for Egyptian museums, comparing traditional POE solutions and frameworks with new proposed framework that incorporates AI-generated alternatives. This study emphasizes the dual role of museums as artifact custodians and platforms for public education about ancient cultures. It highlights the imperative to transform Egyptian national museums into immersive learning environments, rather than mere storage spaces. The aspiration is to create museums that securely display and preserve artifacts while fostering educational engagement in preserving our shared history.

Keywords: *Museum experience, Post Occupancy Evaluation (POE), Qualitative Approach, Artificial Intelligence (AI), Mid-Journey.*

EXPLORING THE INTEGRATION OF MID-JOURNEY AI FOR ARCHITECTURAL POST-OCCUPANCY EVALUATION: PRIORITIZING EXPERIENTIAL ASSESSMENT

ملخص. لقد تطورت عملية تقييم ما بعد الإشغال (POE)، والتي تعتمد تقليديًا على تعليقات وملاحظات المستخدم الشخصية، استجابةً للمخاوف العالمية مثل تغير المناخ والاستدامة. ويعكس هذا التحول نحو قدر أكبر من الموضوعية والقياس الكمي زيادة التركيز على القياس الدقيق للمقاييس البيئية ومقاييس الأداء. ونتيجة لذلك، أصبح التقييم المعماري الآن أكثر توجهاً كمياً، مبتعداً عن التركيز التجريبي في الغالب. يبحث هذا البحث في دمج أداة الذكاء الاصطناعي الناشئة في منتصف الرحلة في عملية POE، ويستهدف على وجه التحديد تقييم الجوانب التجريبية في التصميم المعماري. يقترح أن أدوات الذكاء الاصطناعي يمكن أن تكون مفيدة للمعماريين والمقيمين من خلال ترجمة تعليقات المستخدمين إلى تمثيلات مرئية ورؤى مفاهيمية. تهدف الدراسة إلى بدء خطاب حول دور نماذج تحويل النص إلى صورة في تقييم تجارب المستخدم، ومن المحتمل أن تصبح جزءًا لا يتجزأ من عملية التصميم وتوليد المفهوم. يجمع البحث بين الأساليب الكمية مثل الدراسات الاستقصائية والتجارب المعتمدة على الذكاء الاصطناعي مع الأساليب النوعية مثل الملاحظات والمقابلات لتقديم مقترحات تعزيز للمتاحف المصرية، ومقارنة حلول وأطر POE التقليدية مع الإطار المقترح الجديد الذي يتضمن البدائل المولدة بواسطة الذكاء الاصطناعي. تؤكد هذه الدراسة على الدور المزدوج للمتاحف كأمناء على القطع الأثرية ومنصات للتعليم العام حول الثقافات القديمة. ويسلط الضوء على ضرورة تحويل المتاحف الوطنية المصرية إلى بيئات تعليمية غامرة، بدلا من مجرد مساحات تخزين. يتمثل الطموح في إنشاء متاحف تعرض القطع الأثرية وتحافظ عليها بشكل آمن مع تعزيز المشاركة التعليمية في الحفاظ على تاريخنا المشترك.

الكلمات المفتاحية: *التجربة المتحفية، تقييم ما بعد الإشغال، منهج نوعى، الذكاء الاصطناعى، برنامج ميدجورنى.*

1. Introduction

This paper aims to contribute to the discourse surrounding the role of museums in Egypt by addressing a crucial aspect often overshadowed in the literature – the need for a qualitative Post Occupancy Evaluation (POE) approach. While quantitative parameters such as environmental conditions, energy consumption, and building performance metrics have traditionally dominated discussions of POE, there is a growing recognition that an exclusive focus on these aspects is insufficient. This is particularly pertinent when considering the complex and multi-dimensional nature of the museum experience. It is essential to understand how visitors engage with museums on a deeper level, beyond the quantifiable factors.

Museums in Egypt, renowned for their rich historical treasures, are currently facing a significant challenge in the 21st century. Traditionally, these institutions have been primarily focused on the meticulous documentation of artifacts, sometimes at the expense of effectively conveying the captivating stories they hold. As Zahi Hawass eloquently articulated, the ideal role of museums should extend beyond secure preservation to encompass a broader educational mission. Museums should serve as institutions dedicated to teaching the public about ancient cultures, with a particular emphasis on fostering an understanding of how to learn from and safeguard our common historical heritage.

The selection criteria for museums, including iconic institutions like the Egyptian Museum and the National Museum of Egyptian Civilization, primarily revolve around their intended role and the preservation of national and historical identities. While these two museums share similar mission objectives and overarching goals, they were constructed at significantly different points in history, resulting in potentially distinct impacts on their users. The chronological gap between their construction reflects disparities in technological and conceptual advancements, which may influence the user experience. However, a critical reason for examining both museums lies in the opportunity for comparative analysis. Both the Egyptian Museum and the National Museum of Egyptian Civilization are integral in representing and conveying Egypt's rich history and cultural identity. Understanding and evaluating the user experience in these institutions is vital for capturing the essence of Egypt's heritage and identity, allowing for a comprehensive assessment of their roles as cultural repositories.

This research argues for a shift in focus towards a more qualitative understanding of the museum experience. The study challenges conventional evaluation methods and their limitations in capturing the holistic experiences and user journeys within museum spaces. In an era characterized by significant advancements in architectural design technologies, particularly in the museum typology, there is a notable gap in integrating these innovations into the POE process.

The Integration of the emerging artificial intelligence tool Mid-journey, within the post-occupancy evaluation (POE) process, with a particular focus on evaluating the experiential dimensions of architectural design. The proposal posits that these AI tools can serve as valuable assets for architects and evaluators by facilitating the transformation of qualitative feedback from users into visual representations and conceptual ideas. This method not only enriches our comprehension of user experiences but also holds promise for guiding future design refinements and curatorial strategies. The principal aim of this study is to initiate a dialogue concerning the role of text-to-image models in the evaluation of user experiences, highlighting their potential as integral components within the design process and concept generation framework as well.

1.1. RESEARCH AIM AND OBJECTIVES

The primary aim of this research is to revolutionize the conventional Post Occupancy Evaluation (POE) framework within the context of Egyptian national museums by incorporating basic artificial intelligence tools, such as Mid-journey, with the overarching goal of promoting a qualitative approach.

Revise the Traditional POE Framework: The objective is to redefine the evaluation framework to prioritize experiential aspects and user engagement within museum spaces.

Integrate AI Tools for Enhanced Evaluation: To explore the integration of basic artificial intelligence tools, particularly Mid-journey, into the POE process with a specific focus on evaluating the experiential dimensions of architectural design. This involves translating user feedback into visual representations and conceptual insights, thus enhancing the qualitative assessment of user experiences.

Promote Text-to-Image Models for User-Centric Assessment: To initiate a discourse on the potential of text-to-image models in assessing user experiences within museum spaces. This objective seeks to underscore the role of AI-driven tools as integral components within the design and concept generation process, aiming to promote a user-centric approach to museum evaluation.

Reimagine Museums as Immersive Learning Environments: To explore and articulate innovative strategies to re-envision Egyptian national museums, shifting their primary function from passive artifact storage to dynamic and immersive educational spaces that actively engage visitors in ancient cultural narratives.

1.2. METHODOLOGICAL FRAMEWORK

This research entails a structured approach involving two consecutive Post Occupancy Evaluations (POEs) for two prominent Egyptian museums: the Egyptian Museum in Tahrir Square and the National Museum of Egyptian Civilizations. The initial POE adheres to conventional research methods, encompassing surveys, interviews, and on-site observations, to gather both quantitative and qualitative data. The research methodology comprises five key stages: a comprehensive literature review, the administration of surveys, conducting interviews, gathering in-site data, performing correlation

analysis, and culminating in a comparative analysis of the two museums' designs.
The subsequent POE adopts a more qualitative approach, focusing on intangible design aspects and leveraging surveys and interviews. This evaluation process unfolds in three distinct phases: the collection of descriptive statements elucidating users' experiences, the utilization of the AI tool Midjourney to generate design variations, and the execution of interviews with participants based on AI-generated images. This iterative process serves to refine the translation of design concepts and enhance both the interior and exterior spaces of the Egyptian Museum and the National Museum of Egyptian Civilizations.
The primary objective of the second POE is to showcase the potential of qualitative analysis and to juxtapose its outcomes with those of the initial, more traditional POE. By integrating advanced AI tools and user feedback, this research endeavors to illustrate the value of enriched design assessments that transcend the conventional boundaries of quantitative evaluation, thereby contributing to the discourse on the evolving methodologies of architectural evaluation.

1.3. LIMITATIONS

This research employs a soft simulation of Post Occupancy Evaluation (POE) due to time and resource constraints. Its main goal is to compare traditional and innovative POE methods rather than draw final conclusions. The second POE has limitations in the number of interviewees due to time and resource constraints. Originally a collaborative effort, unforeseen circumstances led to a single-author approach, focusing on a more concentrated discussion. Additionally, the use of Mid-journey introduces a limitation where specific outcomes must be chosen due to time and capacity constraints. These challenges are recognized as inherent in the research process, with the aim of contributing to scholarly discussions rather than exhaustive outcomes.

2. Literature Review

2.1. A REVIEW OF POST-OCCUPANCY EVALUATION

This section offers an academic overview of the history and evolution of Post Occupancy Evaluation (POE), with a focus on critical analysis and positive perspectives. It begins by emphasizing the role of POE in refining design approaches and frameworks. The discussion highlights inherent challenges and limitations, particularly in assessing qualitative aspects of design, and notes how the integration of computational tools has led to a greater reliance on quantitative methods, moving away from the essence of phenomenological evaluation.

Shifting the focus to the phenomenology of architecture and its impact on the design process, this section employs museum typology and museological concepts as illustrative examples. Museums prioritize strong conceptual frameworks and user experiences, necessitating a distinct approach for post-occupancy assessment. Consequently, this literature review segment explores the potential integration of Artificial Intelligence (AI) into the POE and design framework. This integration aims to bridge the gap between design intent and user experience by facilitating the translation of internalized design concepts into tangible outcomes.

Wolfgang F. E. Preiser's contribution to the distinction of Post Occupancy Evaluation (POE) from other building evaluation approaches is discussed. Introduced by Preiser in 1988, POE focuses on assessing various aspects of a building, addressing questions related to its functionality and whether its intended use and materials effectively support its purpose (Preiser, 1988). This approach enables architects to evaluate a building's functionality and accessibility post-occupancy. Building Performance Evaluation (BPE) emerged as an extension of POE (Preiser and Vischer, 2004), encompassing user, aesthetic, technical, and economic factors (Preiser and Schramm, 1997) while assessing a building's primary technical and functional aspects.

Described as a systematic process involving data collection, analysis, and comparison against relevant criteria, POE aims to identify issues, highlight operational gaps, extract lessons for enhancing the design of similar projects, and serve as a benchmark for comparing similar projects over time (Mustafa, 2017). In essence, POE offers a structured approach to evaluate building performance and inform design improvements based on real-world usage and experiences.

2.2. THE IMPORTANCE OF POE & HOW IT CAN AFFECT THE DESIGN APPROACH

Post Occupancy Evaluation (POE) is often referred to as "lessons learned," involving the collection, documentation, and sharing of insights regarding the successes and failures of processes and products. This gradually builds an archive of design experiences, informing designers and their processes. The POE process encompasses three phases: indicative, investigative, and diagnostic. Indicative POE identifies key strengths and weaknesses of a building's performance. Investigative POE delves into the physical performance of a building and how users respond to its functional program. Diagnostic POE involves a comprehensive examination, utilizing methodologies like questionnaires and observations (Preiser, 1988; Lawrence, 2013).

POE serves as a crucial tool for assessing a building's success and testing design hypotheses, creating a feedback loop to inform future designers about best practices. It benefits architects by ensuring user comfort, contributing to the success of client investments, and generating knowledge about the short and long-term outcomes of design decisions, considering factors such as cost, occupant satisfaction, and building performance, including energy efficiency. Ultimately, POE aids in enhancing buildings, improving occupant comfort, and managing costs (Preiser, 1988; Lawrence, 2013).

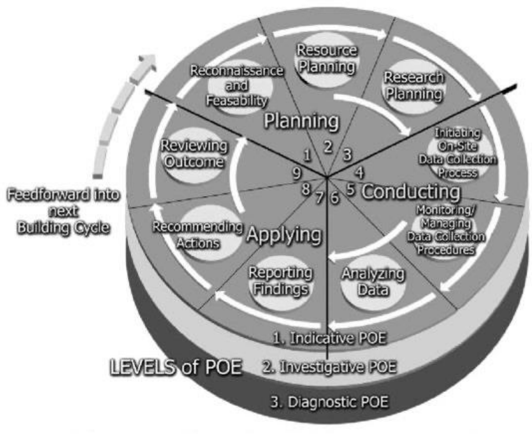

Figure 1. Traditional POE Cycle.

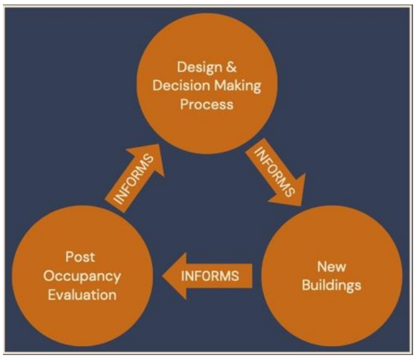

Figure 1. Relation of POE to the Design.

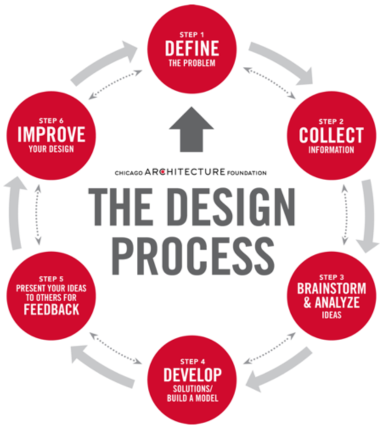

Figure 3. The Design Process.

2.3. CHALLENGES OF POST-OCCUPANCY EVALUATION DESPITE THE TECHNOLOGICAL ADVANCEMENT

The Post Occupancy Evaluation (POE) serves as a solution to assess design deficits in fully operational buildings, offering an auditing tool to measure their effectiveness (Gocer, Hua, 2015). Although well-intentioned, the POE is not without shortcomings due to its human-made nature. Traditional POE methods focus on quantitative aspects of design, seeking empirical data that is easily analyzed and addressed, particularly related to energy consumption and the "green" concept (Gocer, Hua, 2015). This involves techniques like questionnaires, interviews, site visits, and observations of building users (2001).

Challenges arise in conducting effective POE due to the extensive field research required, consuming significant time and resources (Grocer, 2015). While recent advancements in technology and computation tools have improved data collection and analysis, the primary evaluation criteria still revolve around measurable design elements such as daylight, acoustics, thermal environment, energy consumption, and other LEED parameters. The Royal Institute of British Architects (RIBA) defines POE as a systematic study of buildings in use to provide architects with insights into their designs' performance and offer building owners and users guidelines for optimal use (RIBA, 1991).

However, there's a need to balance this quantitative approach with a more human perspective. Architectural advancement, driven by digital tools, has led to faster and more complex design processes, resulting in intricate building typologies serving multiple functions. Amid these developments, it's crucial to focus on the human experience within buildings, not just measurable factors. Architects often lack information about how their designs truly serve occupants, and data-driven clients seek to verify design goals (Kilkelly, 2018). Architecture's foundation in phenomenology emphasizes understanding how users experience buildings, encompassing emotions, expectations, and personal interactions (Gocer, Hua, 2015).

In essence, while POE has evolved with technology, its significance lies in merging quantitative data with qualitative human experiences to comprehensively evaluate building designs and their real-world impact.

2.4. PHENOMENOLOGY AND ARCHITECTURE: QUALITATIVE BUILDING TYPOLOGY

Pallasmaa highlights the importance of experiential connection with the environment in architecture. Phenomenology seeks to create abstract sensory experiences that transcend tangibility, allowing for a deeper meaning. Going beyond physical elements in spatial encounters enhances significance. Buildings and cities offer the lens through which human existence can be comprehended and confronted. Thus, architecture must be approached as a subject of phenomenology. Pallasmaa (1994) contends that a potent architectural experience quiets external distractions, directs attention to our very being, and, like all art forms, raises awareness of our essential solitude.

The preceding section highlights the challenge of evaluating building experiences, despite technological advancements accelerating the conceptualization process. This portion explores the Museum typology as an exemplar of an experience-focused building type, delving into its design and evaluation standards. It then addresses the issue of externalizing and translating emerging concepts. By reimagining the traditional Post Occupancy Evaluation approach and integrating Artificial Intelligence as a design guide tool, the section proposes a shift within the conventional design framework towards greater alignment with the intended design concept and experiential continuity. This redefined approach aims to bridge the gap between design intent and realized experience.

2.5. MUSEUMS NON-STANDARDIZED STANDARDS

Museums play a vital role in connecting individuals to their historical roots and heritage, guided by intricate design standards and diverse approaches (Chenhall and Homulos, 1978). These institutions primarily serve to interpret culture, history, and heritage, functioning as valuable resources for researchers and educational systems, offering firsthand experiences with ancient artifacts (Askari and Altan, 2015). Museum design standards encompass internal preservation functions and external exhibit interactions, influenced by target users, site selection, and collections (Chenhall and Homulos, 1978).

Criteria for site selection align with site conditions and requirements, encompassing categories such as accessibility, parking, solar orientation, and community alignment. To accommodate the diversity of museum sizes, types, and purposes, designers must consider unique features and contexts during concept development. The designer's creative vision plays a pivotal role in shaping the museum to harmonize with the community it serves, reflecting its history, culture, and identity (Chiara and Crosbie, 2001).

Chenhall and Homulos (1978) emphasize the importance of adhering to general museographic principles in museum design, with a focus on thoughtful space arrangement and circulation. This approach aims to achieve harmony between the architectural environment and user needs. Key integrated qualities of successful museum design include accessibility, spatial organization, effective utilization of natural light, layout strategy, display concepts, and the dynamic interaction between exhibits and visitors.

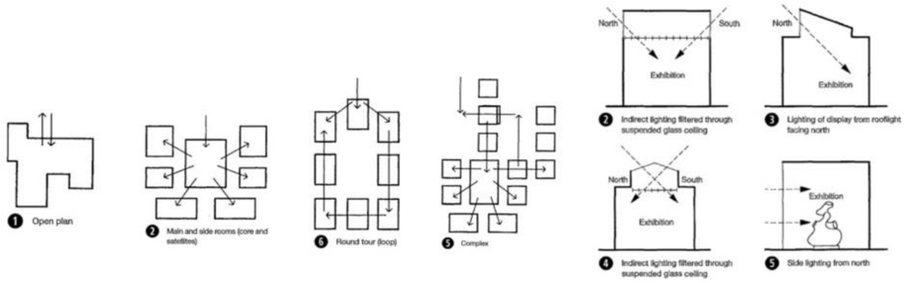

Figure 4. Museum Design Guideline.

Traditional design processes risk losing track of original intentions, leading to moments of misinterpretation and lost creativity. Post Occupancy Evaluation (POE) assesses built structures but often falls short in evaluating intangible aspects. A new POE framework is needed, integrating AI as a tool to better interpret design ideas, preserve original intent, and circumvent design bottlenecks, ensuring successful translation from concept to reality. The objective of this research is to propose an AI-enhanced POE framework that addresses these challenges.

The American Alliance of Museums recognizes the absence of a single set of museum standards, emphasizing the need to draw guidelines from diverse sources (American Alliance of Museums, 2015). These standards primarily emphasize overarching operational principles, offering flexible outcomes achievable through various approaches (Kotler, 2008). Consequently, the success of museum experiences hinges not only on guideline adherence but also on a profound understanding of the museum's purpose, physical attributes, non-physical aspects, and contextual roles (Brodie et al., 2003).

3. Methodology

3.1. OVERVIEW OF THE EGYPTIAN MUSEUM AND NMEC

This part will first introduce the main subjects of this research: The Egyptian Museum and the National Museum of Egyptian Civilization. Those two have been chosen for their very similar objectives and overall intent. They were both designed and built in very different times which makes the comparison intriguing since this time difference plays a big role in the design tools and ideas generated. The second portion of this section will present both conducted POEs. Starting with the traditional evaluation, presenting its criteria, the observations, survey, and interviews as well as their findings. Then followed by the newly proposed POE and its findings.

The Egyptian Museum (EM) was the first purpose-built museum globally, founded by Muhammed Ali Pasha to counteract antiquities smuggling (Abdalla & Abd El-Megiud, 2020). Located in Downtown Cairo, it houses vast historical artifacts and features classical Roman architectural design (Abdalla & Abd El-Megiud, 2020).

Figure 5. The Egyptian Museum

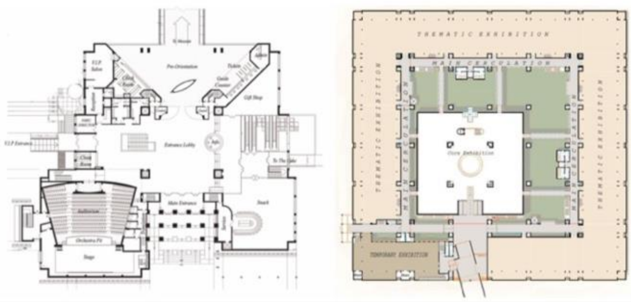

Figure 6. NMEC Layout

3.2. SIMULATION OF A TRADITIONAL POST-OCCUPANCY EVALUATION

The considered standards for evaluation on drawn from three primary sources: UNESCO museum standards, Architect's Data by Neufert, and ICOM standards. The design standards examined earlier resulted in a checklist employed during the walkthrough. The checklist covered various aspects such as the connection between exterior and interior spaces, site-museum relationship, accessibility, circulation, indoor space arrangement, layout, and display concepts, as well as the impact of natural and artificial lighting and acoustics on the indoor experience. Regarding the analysis criteria, the RIBA primer guided the creation of both questionnaires and the observation analysis. This analysis primarily focused on occupant behavior and feedback, environmental performance, and comparisons.

TABLE 1. Multi-criterial analysis

Building Design Qualities	**Indoor Environmental Qualities**	**Building Support Services**
Exterior appearance: Aesthetics, erosion and physical environment of the exterior spaces (elevations, recreational spaces, etc.)	**Thermal comfort:** The state of satisfaction with the ventilation system of the spaces	Washrooms and locker rooms
Interior appearance: aesthetics cleanability, erosion and physical environment of the interior spaces	**Visual comfort:** the quality of indoor lighting both natural and artificial	Food and beverage
Layout type: the connection between spaces, circulation, and accessibility	**Acoustics comfort:** the ambient level of sound and transmission between zones	**Horizontal circulation:** the movement within the building, typically on the same floor level
Display concept: the setup of the exhibits and their relation to narrate a story	Security and fire safety	**Vertical circulation:** stairs, elevators, ramps, etc.

3.2.1. Observational Walkthrough for the Egyptian Museum & the NMEC

The Egyptian Museum serves as a notable illustration of the latter observation. Over the course of more than a century, it has functioned primarily as a repository for newly discovered artifacts. However, its display areas often resemble storage facilities rather than immersive learning spaces. Many exhibits lack clarity and visual engagement, resulting in a diminished appreciation of the artifacts' true value and an overall impression of underrepresentation. Notably, recent efforts have been made to enhance the museum's signage, although some remain challenging to read, despite the inclusion of Braille for accessibility. Furthermore, the recreational areas within the museum do not maximize their practical or experiential potential.

In contrast, the National Museum of Egyptian Civilization (NMEC) employs diverse display methods, encompassing the suspension of artifacts on walls, presentation within boxes, and utilization of the building's structural elements for display and signage purposes. However, the arrangement of the curated space appears somewhat haphazard, despite the attempt to organize artifacts based on their density. This leads to a sense of chaos and disorganization within the space. Multiple types of signage, including interactive screens, display screens, and traditional printed signage, further contribute to the museum's heterogeneous presentation.

Interestingly, the recreational areas in the NMEC exhibit thoughtful design and accommodate various functions. Nevertheless, there remains untapped potential for this facility to evolve from a mere place to visit into a space where visitors are encouraged to linger and engage more deeply with its offerings.

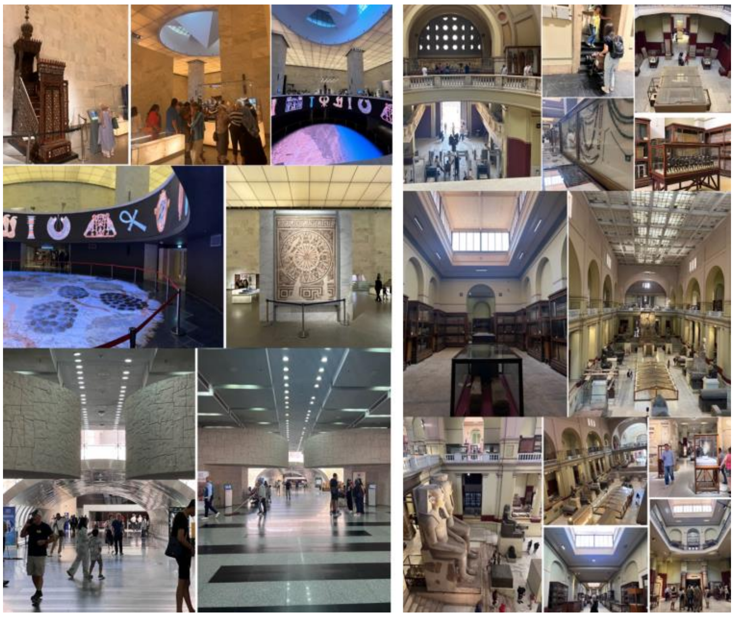

Figure 7. Interior walkthrough of both museums: *Left:* NMEC, *Right:* Egyptian Museum

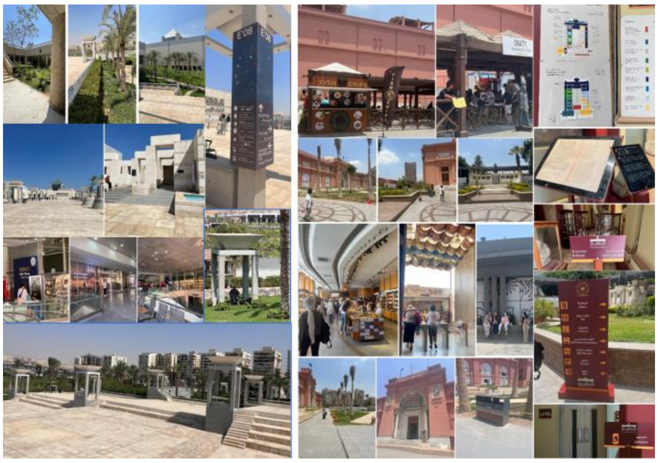

Figure 8. Outdoor leisure/signage of both museums: *Left:* NMEC, *Right:* Egyptian Museum

3.2.2. Survey & Interview Results

The survey results are presented in a comparative format to highlight the major merits or demerits of both regarding the design quality, building support services, and indoor environmental qualities. Questions were designed to avoid conflict in answers by giving them clear options and rating scales.

The survey highlights the large difference between the accessibility of both museums when it comes to the accessibility of the drop-off, another well- noted difference between both is that has been consistent all over, which is the large variation in opinion regarding any of the parameters. For instance, when asking about the services offered, in the EM there is a big variation in the opinion of those taking the survey, however, this variation decreases when the museum in question is the NMEC.

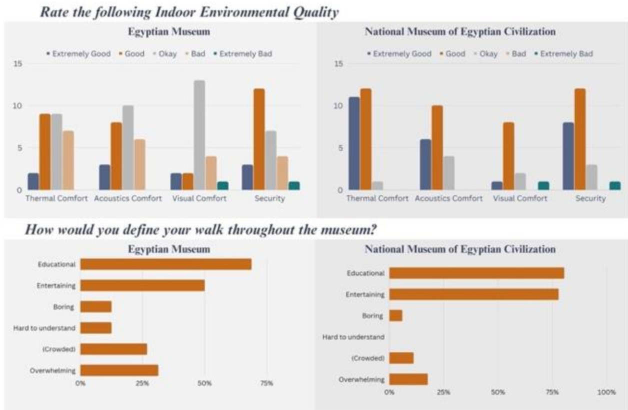

Figure 9. Environment Survey Results

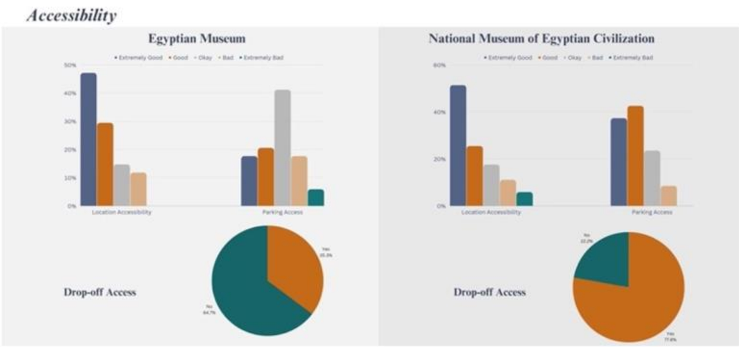

Figure 10. Accessibility Survey Results

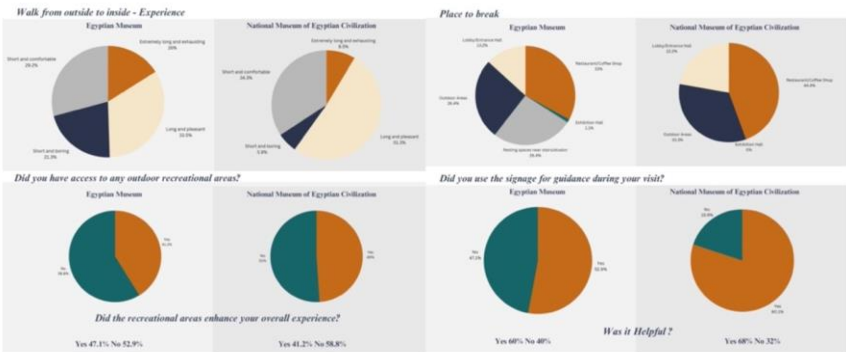

Figure 11. Survey: Design Qualities & Indoor Environmental Qualities

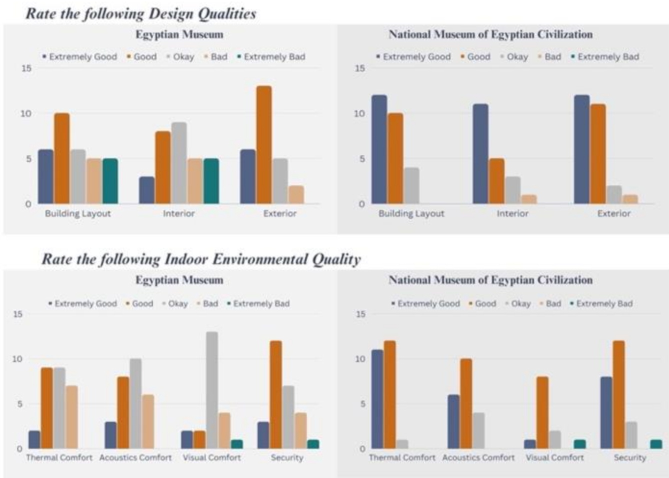

Figure 12. Outdoor Experience

In regards to the design qualities, it is clear that there is a consensus on the decrease in the quality of the Egyptian museum, where most of the surveyed' votes range between “okay” and “bad”. There is a clear division in the opinion of the surveyed regarding the walkability of the museum: almost 50% of both the NMEC and EM found good access to the recreational areas.

The majority of the survey’s results prove that the observations were correct and on point. However, the variation of opinion could be an indication of how people only interpret things differently or that there is some kind of inconsistency in the performance of the museum. Additionally, the weather conditions must not be forgotten because they play a major role in how people find the place to be enjoyable or not. There is also the time parameter which, of course, plays a major role in the perception of the EM, since it is much older than the NMEC.

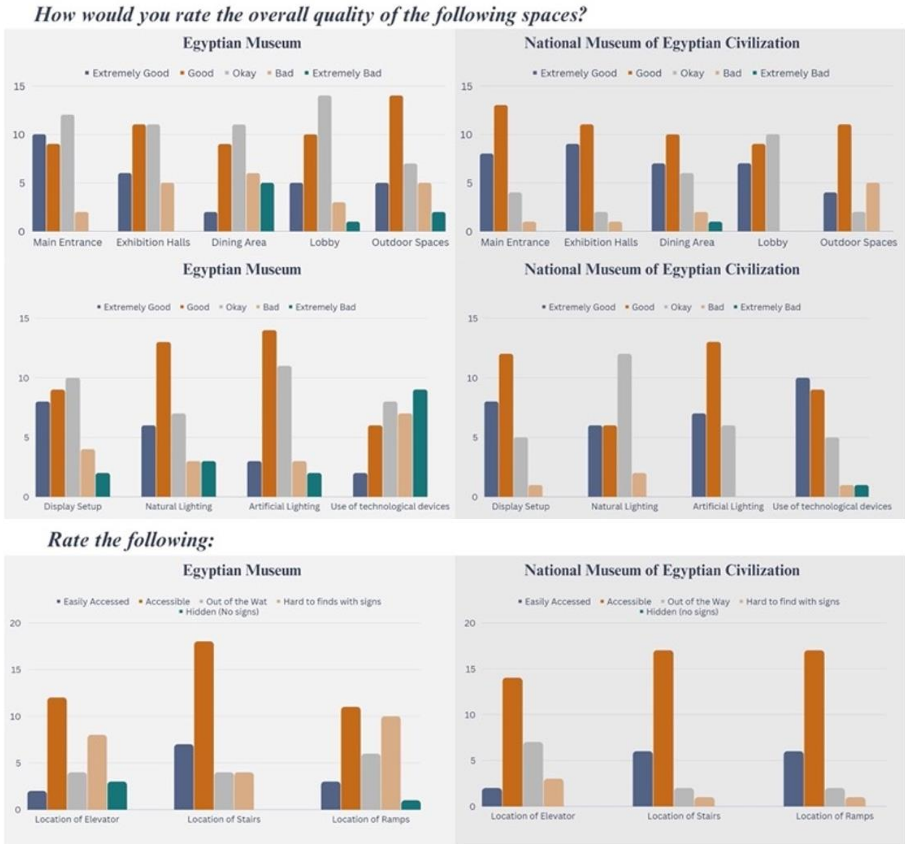

Figure 13. Overall Experience Rating

Three interviews were conducted, one with a staff member and the other with two tourists. The first interview with the chief curator at the NME covered several points regarding their architecture, function, and use of exhibition areas. Further, covered the issues encountering the NMEC and its future potential. The other two interviews took place in the EM, where they discussed their experience as first-time visitors, the overall quality of the museum, signage, and museum facilities. The interviews are summarized in a mind map format found in the appendix.

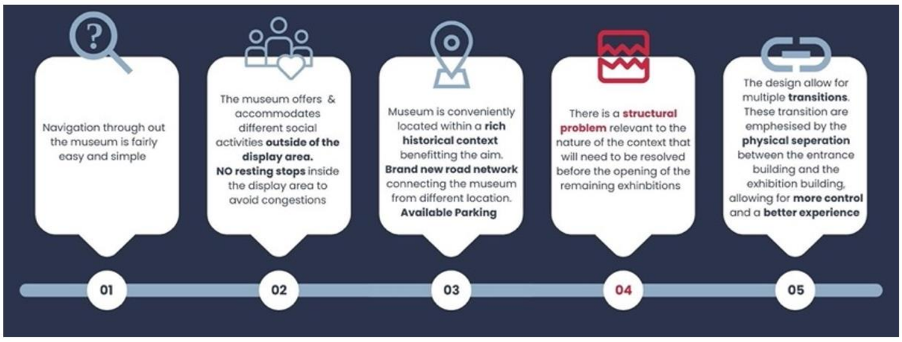

Figure 14. Interview Discussion

3.2.3. Comparative Analysis & Findings

This section compares and analyses both museums based on the previously presented and conducted POE.

TABLE 2. Comparative Analysis EM + NMEC

	Egyptian Museum	**National Museum of Egyptian Civilization**
Building Design Qualities	Given that the Egyptian Museum is 113 years old, the qualities of the building have deteriorated drastically. However, the issue is more relevant to the curation and number of artifacts present. Security has been improved through time by adding fences and more security checks. Quality of outdoor spaces needs to improve. Circulation is well designed however there is a shortage of ramps and elevators.	Design incorporates a lot of the needs and standards of the modern museum, starting by dividing the building into two: a service and an exhibition, to include other functions and storages. Security is more efficient that way as well. However, an issue still exists with the curation of the main hall exhibition. Inclusive circulation and design. Building design qualities represent the aim and objective of the museum appropriately.
Indoor Environmental Qualities	Air conditioning needs maintenance. Lighting needs to be enhanced and	Lighting well utilized artificial and natural. Air conditioning functioning. Exhibitions use

	utilized for the benefit of the exhibition.	sound and music in the background enhancing the qualities of the exhibition. Main hall is very noisy though and chaotic.
Building Support Services	Very poor services starting from the bathroom to the coffee shop. Redesigning required for coffee shop especially as it is newly added as an extension. Outdoor spaces should accommodate different seatings and functions to be part of the exhibition as well.	Services are well designed and located. Outdoor space is too vast and underutilized, and needs to be more integrated and used. Other functions could be added to enhance the experience.

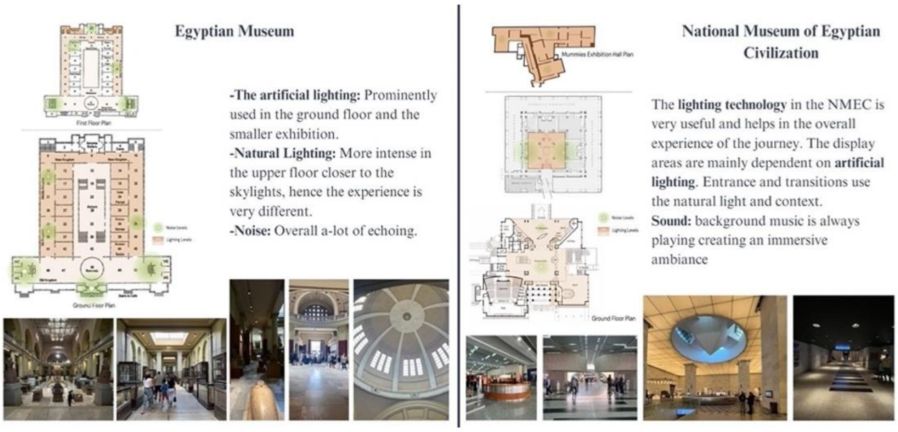

Figure 15. Comparative findings of traditional POE (EM + NMEC)

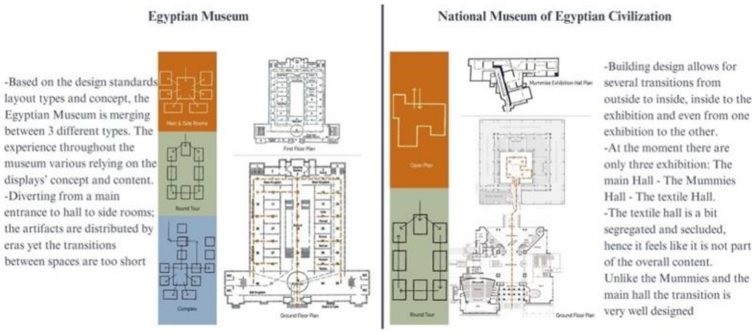

Figure 16. Comparative findings (EM + NMEC): Design Layout & Indoor Environmental Qualities

3.2.4. Human-designed Recommendations and Suggestions

Stacking artifacts is not always efficient. However, since it is a necessity in the Egyptian museum, this research suggests that it would be done purposefully in a methodological way to entice an overwhelming feeling but in that case it is done on purpose as per figure (16). The curation design, in that case, would follow a conceptual design of stacking, and it wouldn't just seem like things were dumped.

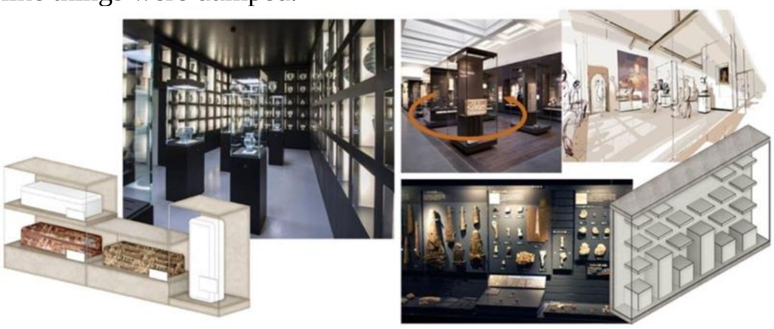

Figure 17. Designed interventions for EM

Figure 18. Interior designed intervention EM

On the other hand, a crucial point in any museum is the service it offers to its visitors. Museums can be tiring and overwhelming; hence the users need to feel at ease and always find a pleasant place to rest and have some coffee or tea. in the EM, the recreational facilities and other services are very poorly designed and overlooked. Even Though there is a huge potential for a much better experience, especially since they are still to be added so there is room for innovation and creativity, the design didn't initially incorporate such services. Some sketches are proposed in previous figures. The idea is to try and incorporate different settings and a variation of indoor and outdoor spaces. Using the context for the benefit of the museum.

The NMEC has proved itself to be a much more improved version, however, it still suffers in the main exhibition hall from an unorganized curation and chaotic display. Even though it is supposed to be more advanced, the display seems more chaotic and doesn't seem to tell a specific story. A little bit of variation in the ambiance is also very much required to adapt for each item on display. However, it is important to note that the technology used for the signage helps a lot more in understanding the content on display. The proposed recommendation in Fig. (17) indicates how some more order and minor partitioning to guide the journey of the users could help in improving the experience.

Bearing in mind that the museum is not fully functioning yet, it is still necessary to highlight that the main exhibition hall lacks the elements of surprise; it is too exposed with no hierarchy. Making the experience all over the place, unlike in the mummy’s hall, where the visitor gets to delve into a whole well-designed ambiance and appropriately curated. The artifacts at hand are looking a little bit poorer and not all seem to be worthy because of the way it is being displayed, or presented, but also because of the large variations in their typologies. However, it is important to note that at the door there are brochures that are being handed out to the visitors, which are extremely helpful for the navigation inside the museum. These brochures are available both in English and in Arabic.

As for the outdoor recreational areas and the indoor services, there is a lot to improve to reach the maximum potential there is for this museum. The outdoor spaces look like a desert in need of shade and accommodation to ensure people get to experience it adequately, as per fig. (18) these interventions need to be done delicately to keep the charming existing design but also to help the visitors spend time there and enjoy it.

Figure 19. Proposed solution for NMEC

Figure 20. Proposed interventions for outdoor area

3.3. SIMULATED SOFT POST-OCCUPANCY EVALUATION

There are two proposed ways to integrate and simulate the Soft POE in this research, the first one is done using a survey and existing images of either the Egyptian Museum or the NMEC. The point of that is to actually use the "statements" resulting from the survey as inspiration and guide for different prompts to feed the Mid-journey along with the image of the place and start generating images that are closer to reality. The other way is actually without feeding the AI any kind of images and using only "prompts" inspired by the interview, like a small descriptive text to let the AI generate what it imagines this text to be. The point of this second proposal is to actually let the AI be used as the conceptualiser, and help in this phase of the design as well. The reasoning in both cases is that this transformation of text-to-image will help designers get closer to what users are expressing through their journeys.

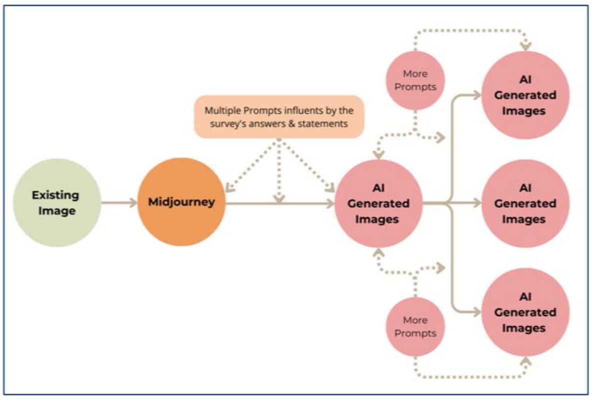

Figure 21. First proposed AI Simulation

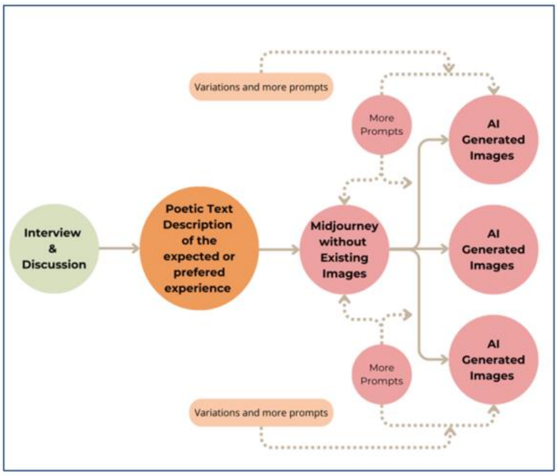

Figure 22. Second proposed AI Simulation

3.3.1. Survey guidelines and findings

The survey was divided into two sections, one for the Egyptian Museum and the other for the NMEC, with identical questions. It commenced by asking participants to envision their museum experience, followed by questions about their actual experiences, both positive and negative. The survey then inquired about post-visit opinions, including potential alterations to the journey.

A set of tables displayed participants' responses, focusing on content-rich statements suitable as prompts for the AI tool Mid-journey. While not comprehensive, the appendix tables highlighted key feedback.

For the Egyptian Museum, participants' expectations section revealed words like "discovering," "scary," "magical," "time capsule," "time traveling," "immersed," and "majestic." These poetic words aligned with the desired ambiance of the museum's design and curation. However, these words could be understood differently by various individuals.

The subsequent sections aimed to organize these keywords, constructing a new Prompt table. This table would form the basis for generating images in Mid-journey, capturing participants' envisioned museum experience based on survey feedback. The experience section for the Egyptian Museum contained negative feedback, which would be reversed to inform alterations. Specific areas with negative impact were identified, guiding image alterations. The AI simulation focused on three zones of the museum: the main entrance hall, upper side corridors (interiors), and the entrance area (exterior). Keywords and prompts would be merged to create variations, with negative qualities and feelings reversed for prompt usage.

TABLE 3. Egyptian Museum keywords for prompts inspired from the resulting statements of the survey

Architectural Character	*Feelings And Emotion*	*Other*
Magnitude – Scale – Grandeur – Connecting	Magical – Discovering – Majestic – Immersed – Interesting	Traveling Back In Time – Time Capsule – Ancestors – Antiques
Monumentality – Surprise	Pride – Impressed – Enlightening – Mysterious – Amazement – Nostalgic – Curiosity – Dazzle	Intellectual
Long – Old – Chaotic – Informative – Display Quality – Differences	Unimpressed/Impressed – Overwhelming – Dead – Boring – Unorganized – Pride – Purpose	--
Random – Organization – Dusty – Brown – Brown – Display Quality	Disappointing – Unorganized	--
Monumentality – Spacious – Organization Of Artifacts	--	--
Light Design – Vibrance – Different Stages -	Different Emotions – Triggering – Whole – Admire -	Triggering – Extra Seats – Better Display – To Accentuate – Enrich

Similarly to the Egyptian Museum, survey results for the National Museum of Egyptian Civilization (NMEC) are presented in the tables below, though not exhaustive. Responses were selected based on relevance and stimulation. All survey answers are available in the Appendix.

In contrast to the Egyptian Museum, the NMEC's experience feedback skewed more positively. Therefore, for the NMEC, the study's focus shifted to the main exhibition hall, the connecting tunnel, and the outdoor entrance area with steps. These images would serve as the starting point for Mid-journey edits.

TABLE 4. NMEC keywords for prompts inspired from the resulting statements of the survey

Architectural Character	*Feelings And Emotion*	*Other*
Structured – Rigid - Human Scale – Diverse – Trajectory – Identity - Mysterious – Futuristic – Chronological -	Vivid – Nomadic – Immersed – Great – Curiosity -	Time Traveling – Unmediated Experience – Hands On Experience - Interesting – Unraveling – Evolution
Connection – Monumental - Continuity – New – Great	Fascination – Intrigue – Pride – Overwhelmed – Amazed – Excitement –Shock	Memorable – Unique – Understating
Impressive – Views – Less Organized – Continuity – Progression	Clarity – Proud – No Experience	Ugliest Entrance – Airport Like – Scattered – Hall Is Like A Cap For The Artifacts – Outddor Is Too Big -
Lack Of Organization – Flow Of Spaces – Not Well Defined – Lighting	Average – All Over The Place – Unbalanced – Annoying -	Lack Of Charm – No Display Concept – Augmented – Scattered
Beauty – Open – Easy Flow – Display Techniques	--	Use Of Technology – Quality – Music
Too Much Light – Story Telling – Cultural	Interactive – Experiential Journey -	Space Understanding – Missing Spatial Experience – Cleanliness – More Artifacts
Creative – Engaging – Shading – Organized – Ambient Lighting -	--	Connected to Context

3.3.2. A Journey through Mid-journey

a. Survey Simulation

This section of the methodology marks the commencement of the Mid-journey explorations, initiating an exciting phase. The first part pertains to both museums, utilizing the filtered keywords and statements obtained from the survey. These served as a foundation for constructing prompts within Mid-journey. By communicating with Mid-journey Bot on discord the process starts first with the text input along with a realistic image of the intended space or building; this is when Mid-journey processes the text input using deep learning algorithms, particularly generative models, to understand the content and context of the text resulting with the generation of four images based on the processed text. This is when the feedback loop begins, by evaluating the resultant images, and deciding which should be the ones to keep and which are not relevant. During the feedback loop it sometimes happen that all images appear to be irrelevant, which indicates that there may be a problem with the designed prompt. Remember that generating images from text prompts, especially with AI models, may not always produce exactly what you envision. It often involves an element of creative interpretation by the model. Experimentation and iteration are key to achieving the desired results. However, it is important to note the following key elements that might guarantee more relevant results, hence prompts should be: Clear and Specific - Include Key Details - Use Adjectives and Adverbs - Be Concise - Provide Context - Avoid Ambiguity.

This leads to the keyword's selection criteria, as stated in previous section was directly related to the later information, choosing words that were more descriptive either of architecture character inside or outside, words that refer to emotions and experiences, and finally any other words that may have relevant quotations.

The subsequent figures illustrate this journey, starting with the original image fed into the AI, followed by the envisioned outcomes. These resultant images are meant to inspire rather than be practically implemented.

Figure 23. Mid-journey simulation for the interior of the EM

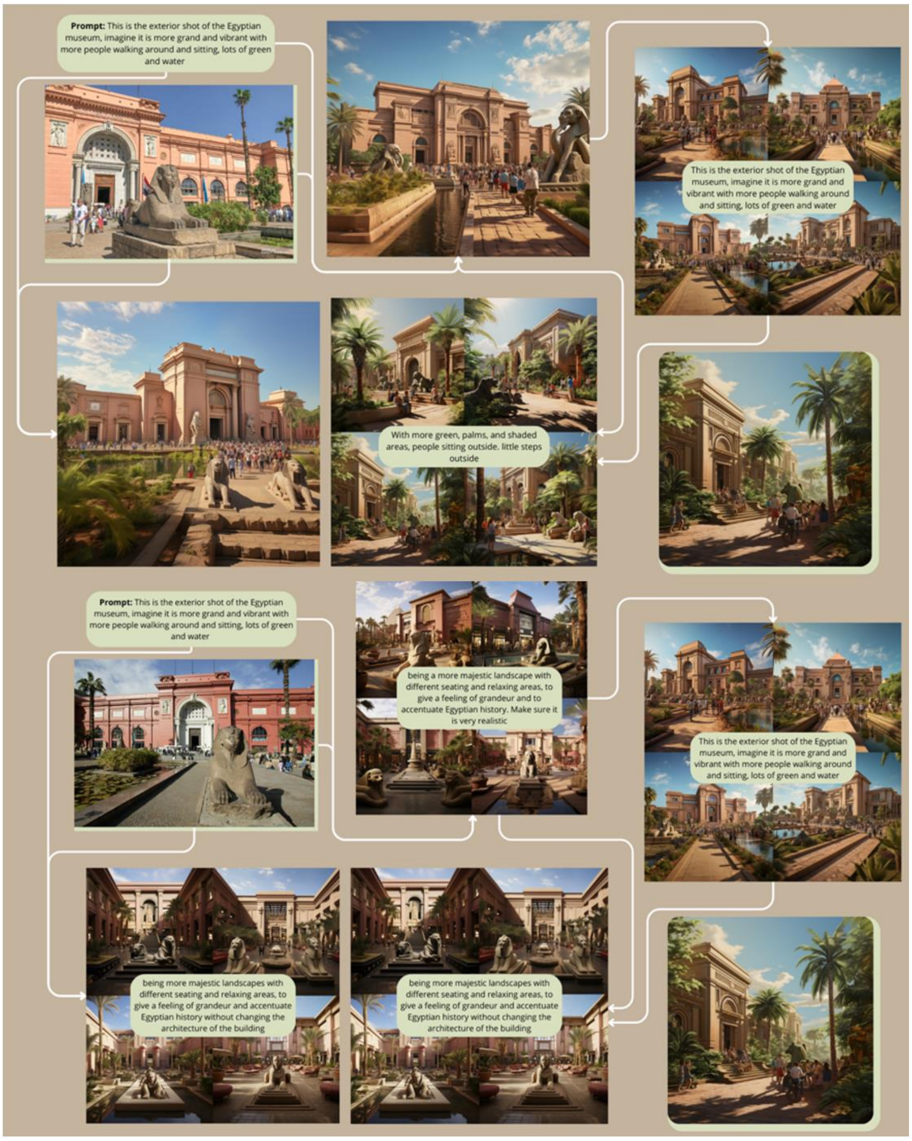

Figure 24. Mid-journey simulation for the outdoor entrance of the EM

Figure 25. NMEC Mid-journey simulation

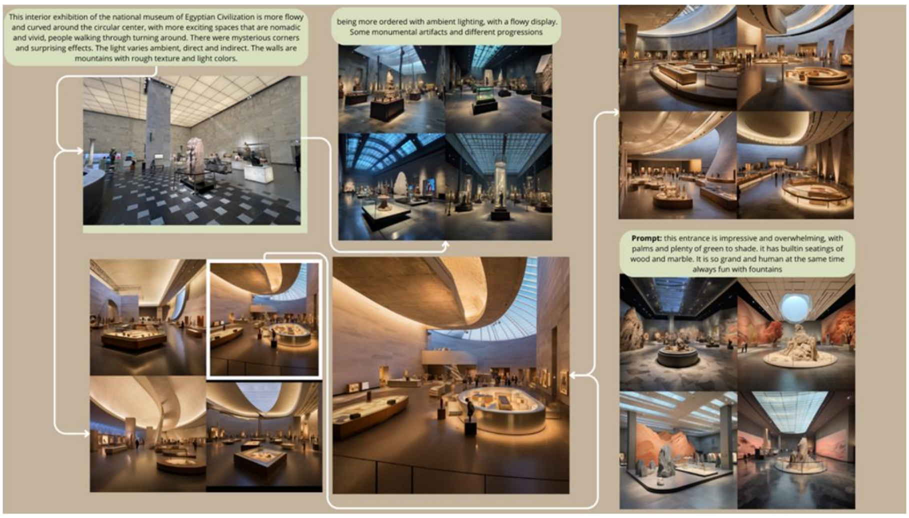

Figure 26. NMEC Interior Mid-journey simulation

b. Interview Simulation

This section presents the second simulation, the following is the text inspired from the interviews. This simulation was conducted solely on the Egyptian Museum as a concept. The section is based on the three previously stated interviews in the first POE simulation is addition to another one conducted only for this second soft POE. The findings of this simulation are mainly limited to inspiration images, that can help as a guide for interventions or during the design phase for future expansions. The Purpose of the interview was to stimulate the mind of the designer, to trigger ideas, and to inspire imagery in the mind of the interviewee to help guide him. Some of the text or ideas inspired for instances where the following figure.

- It's a place where everything dilutes and the past becomes reality. The stories are in the sky, and people dream of the past today.
- A series of Ancient Egyptian antiquities guiding me in a trail to a building that is hidden in between those antiquities, this trail is like (elkebash) The trail is monumental and fragmented.
- There is a sense of evolution and contextuality.
- It's like a dream, words are flying around telling me stories giving me hints.
- The Egyptian Museum is a node a focal point, it is a host for all Egyptology
- It educates and teaches, it's an augmented library
- Each civilization has its own journey, they overlap like lines intersecting and intertwining, there are ups and downs, like floating floors.
- The museum is a journey from outside to inside. A series of antiquities and like the road of the rams. It transports the visitor from one place to another. Magical and Monumental, history fades and augments at the same time.

Figure 26. NMEC Interior Mid-journey simulation

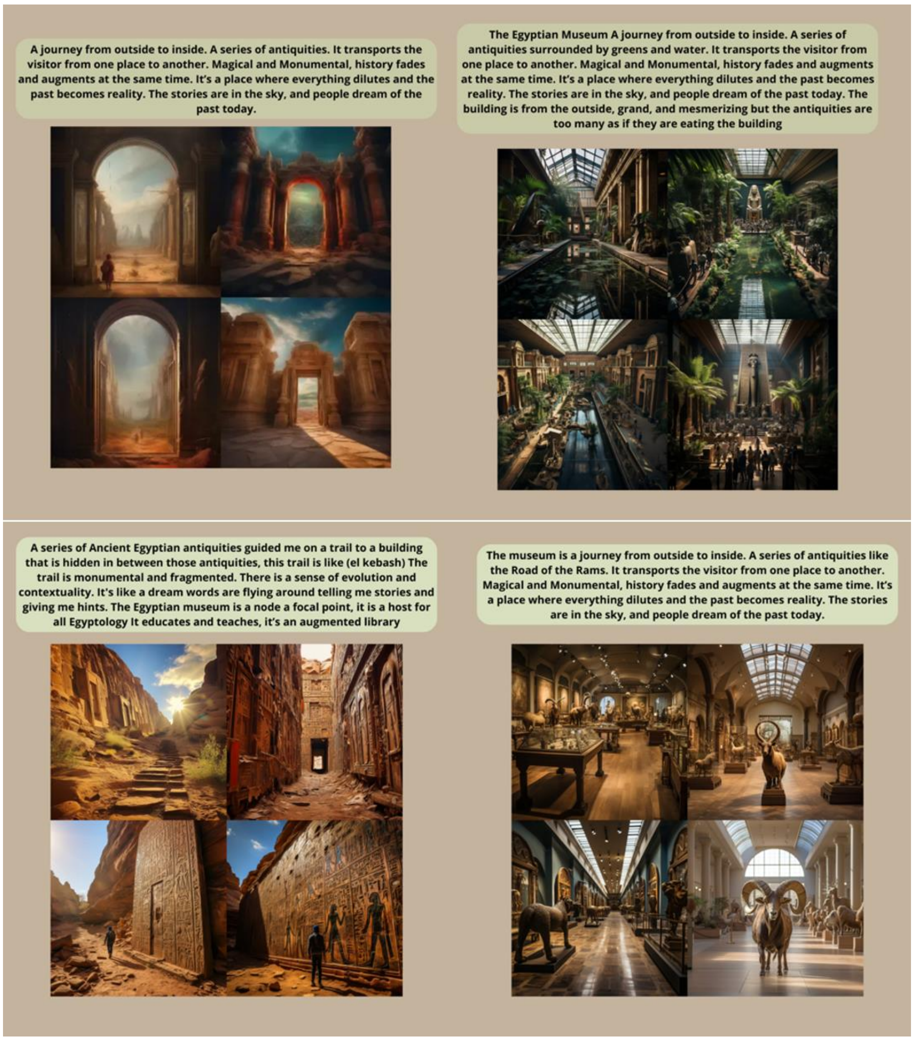

Figure 27. Mid-journey interview simulation for EM

4. Conclusion and Discussion

Museum design standards provide valuable guidelines, yet realizing the full potential of a museum extends beyond mere adherence to these standards. This research conducts a comprehensive Post Occupancy Evaluation (POE) of both the Egyptian Museum and the National Museum of Egyptian Civilization (NMEC), shedding light on their shared objectives despite being designed at different junctures in history. The disparities in public perception and experiential facets are distinctly discernible through a combination of surveys and interviews. This evaluation acknowledges the shifting role of museums, transcending their traditional roles as storage spaces to become multifunctional cultural destinations.

The exploration of Artificial Intelligence (AI) within the context of the POE process reveals the potential of Mid-journey, to serve as a source of inspiration during the design phase. The research underscores that the effective utilization of Mid-journey demands meticulous attention to detail and information. Employing this AI tool necessitates a structured framework, ranging from a comprehensive scope of details to a well-structured mind map or a written mood board. This process encourages designers to consider intricate elements and engage in a trial-and-error approach.

While the generated AI images may appear initially unrelated, their purpose is to facilitate the assessment of user feedback. They act as an intermediary between the designer and the visitor, assisting in the identification of less-appreciated elements within existing spaces. These images offer insights into potential weaknesses in design elements, encompassing physical aspects such as flooring, lighting, color schemes, and landscape, as well as aspects related to arrangement, intensity, order, and chaos.

When engaging in discussions regarding Mid-journey results with interviewees, notable comments emerge, such as "Materiality and lighting made a significant difference," "I felt more engaged even if it's only through the picture," and "The interior feels more inclusive regarding civilizations due to different lighting and qualities." These discussions underscore that the generated images facilitate a common ground for designers and users to delve into more pertinent and grounded details regarding the current museum experience and its envisioned improvements. Moreover, these images offer designers a tangible reference point, serving as a guiding tool to ensure alignment with the intended concept and ambiance.

Nonetheless, two significant drawbacks are identified. Firstly, AI-generated images have the potential to create discrepancies between users' or clients' expectations and actual outcomes, potentially misleading them. Secondly, designers may inadvertently deviate from their original design intent by excessively relying on AI-generated pathways during the feedback loop, given the vast array of possibilities. While AI aims to safeguard design intent, its efficacy hinges on judicious usage, which can yield both positive and negative consequences.

5. Future Prospects and Recommendations

There are very few research papers that discuss both topics together the POE and Computation (Kilkelly,2018). This research is only the beginning of many more possibilities using different tools and approaches. However, there is a great need to look further and find different ways to advance the POE as much as the design process. Assessing and evaluating existing buildings is crucial in this state of the world, not just to assess energy emissions and structures, but those buildings affect humans on a mental level that is beyond all physical states. The way people deal with and understand architecture has always been very complex and has been a subject for debate through time, hence it is our duty to start searching and looking into how to assess our buildings from a more human perspective.

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A MODEL OF SETTINGS FOR HISTORIC PRESERVATION

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Abstract. This study views the historic preservation process as a model of four interconnected settings, normalized here as preservation motive, resource configurations, design role, and project construction. These settings have the potential for more effective exchanges for the benefit of the preservation undertaking. Therefore, we examined the workings of the settings, in general, and explained how the “design role” setting, in particular, can capitalize on such potential. We selected international programs as the data sources and used the comparative approach for analysis. We have concluded that the model works to maintain the wholeness of preservation undertakings. Further, the “design role” setting crystalizes the wisdom of the “preservation motive” and the “resource configurations” settings for re-shaping the building on paper and subsequently, onsite. The results present for historic researchers, resource surveyors, and preservation designers a heightened opportunity for interaction with their counterparts in the setting continuum for increased efficiencies of the preservation process. Firms and workers associated with the settings have the advantage of interpreting and adapting the model to their circumstances.

Keywords: *Model of settings, preservation motive, resource configurations, design role, project construction.*

ملخص. تنظر هذه الدراسة إلى عملية الحفاظ على التراث التاريخي كنموذج لأربعة أطر مترابطة، وتشمل دافع الحفاظ، وتكوينات الموارد، ودور التصميم، وتشييد المشاريع. وتتمتع هذه الأطر بإمكانية إجراء تبادلات أكثر فعالية لصالح جهد الحفاظ. ولذلك، قمنا بفحص عمل الأطر بشكل عام، وشرحنا كيف يمكن لإطار "دور التصميم" على وجه الخصوص الاستفادة من هذه الإمكانات. اخترنا البرامج الدولية كمصادر للبيانات واستخدمنا النهج المقارن للتحليل. وخلص البحث إلى أن النموذج يعمل على الإبقاء على شمولية جهد الحفاظ. علاوة على ذلك، فإن إطار "دور التصميم" يبلور الحكمة من "دافع الحفاظ" وإطارات "تكوينات الموارد" لإعادة تشكيل المبنى على الورق ثم بعد ذلك في الموقع. تقدم النتائج للباحثين التاريخيين، ومساحي الموارد، ومصممي الحفاظ على التراث فرصة متزايدة للتفاعل مع نظرائهم في

استمرارية الإطار لزيادة كفاءة عملية الحفاظ. تتمتع الشركات والعاملون المرتبطون بتلك الإطارات بميزة تفسير النموذج وتكييفه مع ظروفهم.

الكلمات المفتاحية: *نموذج الإطارات، دافع الحفاظ، تكوينات الموارد، دور التصميم، تشييد المشاريع.*

I. Introduction

I.1. TOPIC BACKGROUND AND RATIONALE

Historic preservation is set in the motivating notion of cultural significance. The discipline goes about researching, identifying, designing, and "constructing" heritage resources based on this cultural notion. The discussion of historic preservation as one of the eight cardinal building design objectives in the Whole Building Design Guide (2023) attests to these four functional areas. We normalize these areas as the "settings" for the proposed historic preservation model (Figure 1).

- Setting 1, the Preservation Motive, deals with the cultural values underlying the rationale for protection (Avrami et al, 2019).
- Setting 2, the Resource Configurations, deals with the spatial and physical data that inform the preservation design (Ioannides et al, 2018).
- Setting 3, the Design Role, deals with planning the changes into the resource through the preservation design, a paradigm governed by the preservation standards (Bourdeau et al, 2020).
- Setting 4, the Project Construction, deals with implementing the changes in the field as planned by the preservation design (Sementsov et al, 2020).

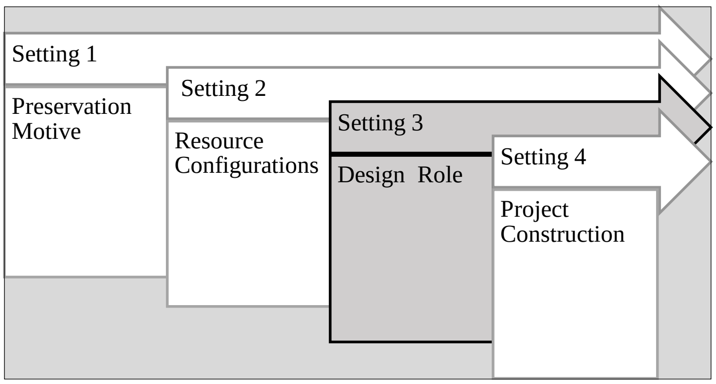


Figure 1. The model of four settings showing complementary characteristics

Settings engage in preservation projects in their own paradigm of understandings, practices, and cultures. Setting actors generally have a cognition of the role of counterpart settings. Seen from the design role viewpoint, “successful preservation design requires early and frequent consultation with a variety of organizations and close collaboration among technical specialists, architects, owner/occupants, and preservation professionals.” Success implies tapping on the potential for exchanges between the preservation professionals acting in the four settings.

I.2. RESEARCH CLAIMS AND QUESTIONS

We advance two claims: first, understanding that the workings of the model settings would augment the efficient exchanges between the model settings; second, bringing the workings of Setting 3 (Design Role) into focus provides a platform where setting exchanges come together to shore up the success of the project. In line with the claims, this study aims, first, at examining the workings of Settings 1 (Preservation Motive) and Setting 2 (Resource Configurations); and second, at explaining how Setting 3 (Design Role) capitalizes on the wisdom and products of Settings 1 and 2.

I.3. RESEARCH SOURCES, METHODS, AND ORGANIZATION

This qualitative study consults a variety of literature sources including journal publications, heritage agency policies, and project reports. For comparative purposes, the study consults the work of some country heritage organizations including Australia ICOMOS, Archaeological Survey of India, US National Register of Historic Places (NRHP), and Historic American Buildings Survey (HABS). The data analysis employs the comparative approach but also, to a lesser degree, employs the expository and interpretive methods.

The study is situated within the context of the international theory and practice related to Settings 1, 2, and 3. The discussion follows the organization shown in Table 1.

TABLE 1. Research Approaches and Sources of Information

Setting	*Scope/Focus*	*Approach*
Setting 1, Preservation Motive	Historic research for corroborating resource significance	Primarily comparative: Heritage resource significance evaluation as prescribed by the US National Register of Historic Places (NRHP) and the Australia ICOMOS
Setting 2, Resource Configurations	Measured surveys for confirming spatial configurations	Primarily comparative: Measured survey as described by the US HDP Historic

		American Buildings Survey and the Archeological Survey of India
Setting 3, Design Role	Design process that adheres to preservation standards and guidelines	Expository and interpretive: Standards and guidelines as described primarily by the US Technical Preservation Services Division

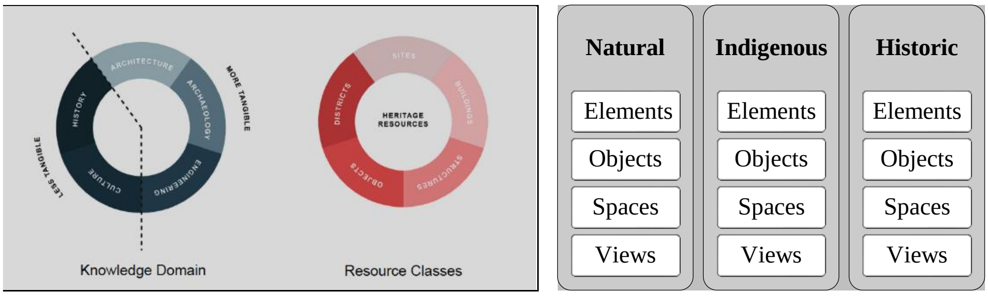
2. Setting 1. Preservation Motive

Heritage motives intertwine with community values. Instrumentalizing motives in service of preservation plans and projects begins with understanding the relationship between community values, cultural significance, preservation standards that safeguard significance, and treatment guidelines that interpret and facilitate the application of standards. We discuss cultural significance here and discuss preservation standards and treatment guidelines in Setting 3. Under this setting, we consider the categories of resources, criteria for evaluating significance, and significance evaluation process; we contrast the US National Register of Historic Places, and Australia ICOMOS.

2.1. RESOURCE CATEGORIES AND SIGNIFICANCE CRITERIA

2.1.1. Categories of Resources

To understand heritage resources, heritage programs begin with establishing resource topology. The National Register asserts "American history, architecture, archaeology, engineering, and culture" as the knowledge domains of endeavor where heritage values dwell. The Register further asserts that "districts, sites, buildings, structures, and objects" (NPS NRHP, p. 2) manifest such cultural values, declaring that these are the five classes of resources any built heritage item may come under (Figure 2, a). Australia ICOMOS states that cultural significance attaches to "natural, Indigenous and historic places with cultural values." Associating place with "geographically defined area," the organization asserts that a place "may include elements, objects, spaces and views," and that "place may have tangible and intangible dimensions" (Figure 2, b). While the National Register defines specific categories of resources relevant in the described fields of endeavor, Australia ICOMOS defines the resources in terms of having significance in the overly broad categories of natural, Indigenous, and historic places.



(a) (b)

Figure 2. Categories of resources considered: (a) By the National Register;*
(b) By ICOMOS Australia
*Source: Elwazani et al (2018)

2.1.2. Criteria of Significance

Identified heritage resource types provide the tangible context for evaluating significance. The contrasting format of Table 2 helps distil similarities and differences between the National Register and Australia ICOMOS significance criteria. The National Register identifies the criteria with a closer affinity to the action (effect) while Australia ICOMOS identifies the criteria in more holistic terms, such as historical values and aesthetic values.

TABLE 2. Comparison of Significance Criteria: US National Register and Australia ICOMOS*

US National Register Criteria for Evaluation	*Criterion No.*	*Australia ICOMOS Criteria for Evaluation*
Events/trends in history	1	Historical value
Leading persons	2	Aesthetic value
Eminent creations	3	Social value
New knowledge	4	Scientific value

* Source: Elwazani, 2017.

2.2. EVALUATION PROCESS

Building on a research design that integrates historical investigation methods and resource site surveys, the evaluation process for the National Register and Australia ICOMOS shows below.

2.2.1. The US National Register Program

The National Register situates the evaluation process of historic resources within the "historic context," a concept by which significance can be evaluated reliably (NPS NRHP. Bulletin 15, p. 7). Historic context is described as “those patterns or trends in history by which a specific occurrence, property, or site is understood and its meaning (and ultimately its significance) within history or prehistory is made clear” (NPS NRHP. Bulletin 15, p. 7). The steps for evaluating the significance of a historic resource depict below (NPS NRHP. Bulletin 15, p. 7).

1. What facet of prehistory or history does the resource characterize?
2. Is that facet significant?
3. Does the resource belong to a type relevant in illustrating the historic context?
4. In what ways does the resource demonstrate history?
5. Does the property possess the physical configurations that convey “the aspect of prehistory or history with which it is associated?

2.2.2. The Australia ICOMOS Program

The Australia ICOMOS program sets the “understanding” of significance as the first cardinal phase of the entire conservation process. It paves the way for policy development and for plan management, the second and third phases of the preservation process. Understanding significance focuses on understanding the place, the spatial context; and, on the cultural values that the place carries (Figure 3).

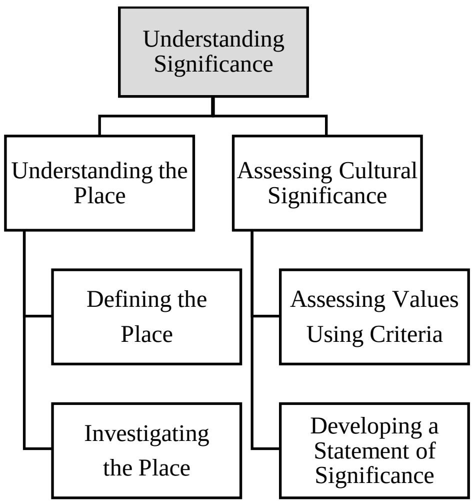


Figure 3. The Australia ICOMOS Process: Steps of the first phase, “understanding Significance”

This phase begins with collecting and analyzing information about the place to glean the attribute of significance. It begins with a) defining the place in geographic, spatial sense to demarcate its boundaries, size, and features; b) examining the main aspects of the place including historic events and trends, use, materials, and association.

2.3. OUTPUT AND USE

The core piece that expresses the output of Setting 1 is invariably the statement of significance that asserts the qualifications of the asset under consideration for inclusion on the heritage inventory. This statement dominates a nomination form, an instrument that frames the recommendation for listing, used in the American and Australian approaches. This form further incorporates a category of general identification information about the resource and another describing the physical configurations and conditions of the resource.

The output value of Setting 1 (Preservation Motive) depends on how well the research team has dealt with a set of attributes such as review quality, stakeholder considerations, and information accessibility. This question is entertained below by contrasting the American and Australian practices.

2.3.1. US National Register

The quality of significance review of heritage places in the United States passes through diligence at the local, State, and national level. The process begins with the owner and the "preparer" of the nomination form at the local jurisdiction's level, moves to the State Historic Preservation Officer (SHPO), and ends at the National Register offices in the National Park Service (Figure 4, a). Conceptually, the nomination process is linear, but operationally, it is reiterative in the flow of information, feedback, and review events. The review process involves the certification by the SHPO that the property meets the National Register criteria for evaluation and eventually ends with the National Park Service certification that the property is entered in the National Register.

2.3.2. Australia National List

The attestation of the quality of significance in Australia undergoes a series of reviews slightly different from that in the US. "Anyone can nominate a place with heritage values for the National or Commonwealth Heritage Lists." The nominator/preparer of the nomination interact directly with Heritage Branch, Department of Climate Change, Energy, the Environment and Water through no intermediary (Figure 4, b).

The nominations that meet eligibility requirements are transmitted to the Australian Heritage Council. The council establishes a priority list of nominations, and when approved by the Minister, the list is posted for public comments. Further, the Council ensures consultations with the applicable owner, occupier, and First People parties associated with the place.

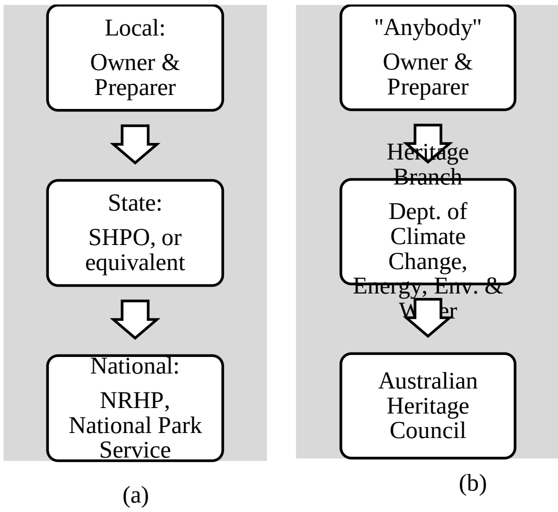


Figure 4. Parties of the heritage resource review: (a) in the National Register Nomination process; (b) in the ICOMOS Australia nomination process

3. Setting 2: Resource Configurations

3.1. OVERVIEW.

Measured surveys and resource condition assessment, the constituents of this setting, provide the spatial and condition documentation needed to drive intervention changes into the "as is" building, being maintenance, repair, or replacement of materials, systems, features, or spaces. Measured surveys of buildings invariably produce scaled drawings, photographs, and descriptive data that are spatial information tools to guide preservation design. Condition assessment of the building is a parallel activity to measured survey, and assessment information helps guide decision making in Setting 3, Design Role as to what preservation treatment type to follow. This activity benefits from a set of the building measured drawings if one is available. As the focus in this study is on measured survey, condition assessment is only asserted as part of the process without elaboration.

How measured surveys are pursued by international heritage programs? Below, we discuss and compare between the US Historic American Building Survey (HABS), and the Archaeological Survey of India (ASI).

III.2. HISTORIC AMERICAN BUILDING SURVEY (HABS)

HABS is a constituent unit of the Heritage Documentation Programs of the National Park Service, together with the Historic American Engineering Record (HAER) and Historic American Landscape Survey (HALS). Work "produced through the programs constitutes the nation's largest archive of historic architectural, engineering, and landscape documentation." The triad program structure reflects a categorized understanding of the resources for documentation purposes, but the programs share common values, methodologies, and user's guidance. The requirements for conducting documentation work all emanate from the Secretary of the Interior's Standards for Architectural and Engineering Documentation. The Standards are interpreted through guidelines that moderate a set of four relationships: content vs. significance, accuracy vs. resource reliability, durability and reproducibility vs. presentation artifacts, and clarity and conciseness vs. communication. These guidelines apply to measured drawings, photography, and written data. Table 3 explains only the "content vs. significance" relationship as applied to drawings, photographs, and written data and expressed in Levels I, II, and III (Federal Register, 2003).

TABLE 3. HABS Documentation Levels*

	Level I	*Level II*	*Level III*
Measured Drawings	"full set of measured drawings depicting existing or historic conditions"	"select existing drawings" to be treated for production.	Sketch plan
Photographs	"photographs with large-format negatives of exterior and interior views"	"photographs with large-format negatives of exterior and interior views, or historic views…"	"photographs with large-format negatives of exterior and interior views"
Written Data	"history and description"	"history and description"	"short form for historical reports"

* Data extracted from the source.

Besides serving as "a permanent record of the growth and development of the nation's built environment," HABS documentation provides professionals, including architects and engineers, with wide-ranging information on historic buildings, structures, and other resources (Federal Register, 2003). Information like what Table 3 invites the discretion of a preservation design team on what level of documentation may be needed based on the significance of the project resource tempered with functional or other considerations.

3.3. ARCHEOLOGICAL SURVEY OF INDIA (ASI)

The Archaeological Survey of India (ASI) is the primary organization for archaeological research and the safeguarding of cultural heritage in India. The standards and recommendations of this organization deals with examination, analysis, and preservation of India's cultural heritage (p. 5). The resources classify according to significance into Grades 1, 2, and 3, reflecting the level of care to be accorded to the resources, including measured survey documentation. The ASI documents follow a holistic narrative approach for dealing with heritage resources, accordingly, measured survey and condition assessment (Setting 2) are discussed in such context.

The documentation dimensions of content, quality, material, and presentation involve and moderate the site's history, architectural features, and significance, with the aim of offering a comprehensive understanding. (Tata Trusts, 2021, pp. 32-39). The standards of the above dimensions safeguard the durability, accessibility, and clarity of documented materials.

The documentation approach by National Institute of Urban Affairs (2013) as applied to Grades I, II, and III is outlined in the Table 4.

TABLE 4.* ASI Documentation Levels defined by Grade of Significance

	Grade I	*Grade II*	*Grade III*
Measured Drawings	- National significance - Full set of drawing	- Regional significance - Representative set	- Local townscape significance - Nominal set
Photographs	- High-quality photographs capturing elements of national significance - Extensive documentation	- High-quality photographs capturing elements of regional significance - Sufficient documentation	- Photographs capturing elements of local significance - Minimum documentation
Written Data	Extensive written data on history and conditions	Comprehensive written information for intelligent conservation	Flexible guidelines for intelligent conservation, supporting adaptive reuse

* Adapted from the source

4. Setting 3, Design Role

How can a preservation design team best utilize the output intelligences of the significance evaluation work (Setting 1, Design Motive) and resource configurations work (Setting 2, Resource Configurations) of the project to consummate the preservation design? Such output intelligences situate the preservation design team to choose the appropriate preservation treatment, and subsequently, to plan a course of action to implement the treatment.

4.1. CHOOSING THE TREATMENT

What kind of treatments are there for the designer to contemplate and choose from? According to the Secretary of the Interior Standards (Technical Preservation Services) treatments classify into four categories: preservation, rehabilitation, restoration, and reconstruction. To explain the treatment genre, we elaborate on preservation and rehabilitation. *Preservation* employs "measures necessary to sustain the existing form, integrity, and materials of an historic property." In contrast, *rehabilitation* makes "possible a compatible use for a property through repair, alterations, and additions while preserving those portions or features which convey its historical, cultural, or architectural values."

A set of standards governs each treatment type defining the requirements for an aspect of the intervention work, for example, "distinctive materials and features." As all standards cater for resource significance and configuration integrity, some requirements echo similarly across the treatment types. For example, the standard governing property use is common between the Preservation Standards and Rehabilitation Standards, leaving room for unique requirements to distinguish between the two. Rehabilitation Standards uniqueness, for example, lies in dealing with new additions and exterior alterations.

TABLE 5.* Considerations for the selection of treatment type for a preservation project

Consideration	*Notes on treatments favored*
Significance level	- Exceptionally significant buildings favor preservation or restoration - Less significant buildings accommodate rehabilitation
Physical condition	- Financial interest of the owner favors rehabilitation; rehabilitation is probably the most common treatment - Resources that are no longer extant or are severely debilitated favor reconstruction
Proposed use	- Visual character that conveys the building's historical significance favors preservation - Alterations or a new addition for a new use favor rehabilitation
Regulatory requirements	Work influenced by regulatory requirements invites the discretion of the designer sensitive regardless of the treatment type as the necessary modifications would not preserve the building's historic character.

* Considerations reflect the Secretary of Interior Standards, National Park Service

Besides the permeating agency of significance across the treatment types, other considerations come into play to sway the selection decision in favor of one treatment or another, including the resources' physical conditions, proposed use, and regulatory requirements. Taken singularly, these considerations tend to favor the treatments as shown in Table 5. Taken collectively, the competing requirements of the considerations will lead to a decision on which treatment to use.

4.2. TREATMENT COURSE OF ACTION

Once the treatment for a historic resource—say, a building—is determined, what course of action does the design team need to follow within the boundaries of the "selected" treatment requirements? To illustrate, it is sufficient here to touch on the course of action in the context of one treatment as a representative example. We opted for the rehabilitation treatment as it is common in use and comprehensive in scope.

At this preparatory stage of the "rehabilitation" project, the design team has a set of information at its disposal, as listed below:

- The building's spatial characteristics in terms of scaled set of drawings for the building and site and supporting photographs.
- Condition assessment results of materials, systems, and features.
- The form and detailing of those architectural materials and features that are important in defining the building's historic character.

In our setting model, these information items are mostly products of Setting 2 (Resource Configurations), which have been, in turn, produced under the auspices of significance (Setting 1, Preservation Drive).

The design team now considers the reductive principle of the preservation theory, which asserts the value of practicing maintenance before repair, and repair before replacement. These measures articulate clearly in the Secretary of the Interior's Standards: a) protect and maintain historic materials and features, b) repair historic materials and features, and c) replace deteriorated historic materials and features.

With the set of information mentioned above in hand, and with an eye on the reductive preservation principle, how should the intervention action into the building progress? Would one start with the building exterior then moves to the interior; or start with the main façade and moves to other elevations; or start with a type of building material or feature (say, masonry or a roof) and moves to the next? Considering a building material or feature approach offers opportunity for consistency and efficiency. This approach is established in the US model. In implementation, the design team goes through basic steps: first, identifies and lists the items of "material types, features, and systems;" and second, determines the level of intervention into the item—maintain, repair, or replace.

We will use the "masonry" item to illustrate one example each for the maintenance, repair, and replacement options. And for each example, we will express the choice in terms of "recommended" action and "not recommended" action (Table 6). The masonry family is taken to include stone, brick, terra cotta, concrete, adobe, stucco, and mortar.

TABLE 6.* Singular examples of "recommend" and "not recommend" under the choices of maintain, repair, and replace for the masonry materials

Maintain	
Recommended	Not Recommended
Cleaning soiled masonry surfaces with the gentlest method possible, such as using low-pressure water and detergent and natural bristle or other soft-bristle brushes.	Cleaning or removing paint from masonry surfaces using most abrasive methods (including sandblasting, other media blasting, or high-pressure water) which can damage the surface of the masonry and mortar joints.
Repair	
Recommended	Not Recommended
Repairing masonry by patching, splicing, consolidating, or otherwise reinforcing the masonry using recognized preservation methods.	Removing masonry that could be stabilized, repaired, and conserved, or using untested consolidants, improper repair techniques, or unskilled personnel, potentially causing further damage to historic materials
Replace	
Recommended	Not Recommended
Replacing in kind extensively deteriorated or missing components of masonry features when there are surviving prototypes, such as terra-cotta brackets or stone balusters, or when the replacement can be based on documentary or physical evidence. The new work should match the old in material, design, scale, color, and finish	Replacing an entire masonry feature, such as a column or stairway, when limited replacement of deteriorated and missing components is appropriate.
* Considerations reflect the Secretary of Interior Standards, National Park Service	

5. Conclusionary Observations and Discussions

5.1. CONCLUSIONARY OBSERVATIONS

General conclusionary observations as well as observations related to Settings 1, 2, and 3 were made.

5.1.1. General Observations

The model builds on the synergic efficiencies between the settings. The complementary and consequential nature of the preservation work underscores the interdependent relationship of the settings in the continuum model. This interdependency, in turn, underscores the need for maintaining the wholeness of the preservation undertakings. Setting 3 (Design Role), that of the preservation design team domain, is prevalent in effecting the project by crystallizing the wisdom of Settings 1 (Preservation Motive) and 2 (Resource Configurations) towards re-shaping—on paper—the building form, materials, and features; and by demarcating the boundaries for on-site treatment, the domain of Setting 4 (Project Construction).

5.1.2. Observations Related to Setting 1, Preservation Motive

The ethereal community values on heritage resources are typically accommodated through the resource's statement of significance. The significance construct transmutes through standards, which, in turn, are facilitated by a set of guidelines—fundamental parameters describing what to do or not to do when treating the fabric and context of the resource under consideration. The step process of significance evaluation coagulates into an output of various documents and formats that epitomizes the function of Setting 1 (Preservation Motive) that, in turn, guides the project throughout the subsequent settings. The heritage asset under consideration is the first beneficiary of the evaluation process's outcome through admission into the jurisdiction's official heritage list or inventory.

5.1.3. Observations Related to Setting 2, Resource Configurations

Measured surveys and condition assessment, the domain of Setting 2, Resource Configurations, provide the spatial and condition documentation needed to drive intervention changes into the "as is" building, being maintenance, repair, or replacement of materials, systems, features, or spaces. For historic buildings, the effect of cultural significance, worked out in Setting 1, Preservation Motive, overarches Setting 2 to regulate the content and accuracy of this setting products.

5.1.4. Observations Related to Setting 3, Design Role

In their design role of Setting 3, design teams revert to the intelligences of the former Setting 1 (Preservation Motive) and Setting 2 (Resource Configurations) to map the fate of heritage assets they are entrusted with curating. The model's overlapping and sequential settings smoothen out the flow of the intelligences. In terms of intervention into the spaces, fabric, and physical features of the resource, such mapping is expected to resolve what to maintain, repair, remove, or add to the resource's physical entity in such a way as to not breach the cultural significance and the spatial and physical integrity. These resolutions, typically conveyed in a set of plans and technical specifications for bidding, move the preservation project forward into the realm of Setting 4, (Project Construction).

5.2. DISCUSSION

5.2.1. Delimitations

The content covered and the methods used for the discussion were attuned to the study objectives, delimiting extraneous matters. For example, Setting 4 (Project Construction) has been asserted as an inseparable member of the setting continuum, but the setting content is left out because it is not within the realm of the study objectives. Further, condition assessment of materials, systems, and spaces was asserted as part of Setting 2, but was not discussed because of the enormity of the subject in relation to the finite capacity of the study. Methodically speaking, the country programs set for the comparative accounts of Settings 1 and 2 were limited only to two, with sufficient information but with moderated effect to control the scope of the study.

5.2.2. Implications

The results have implications for the model setting disciplines of endeavor, including historic research and assessment, measured survey and field investigations, and preservation design. The results present for the built environment historic researchers, resource surveyors, and preservation designers a heightened opportunity of interaction with their counterparts in the setting continuum for increased efficiencies in the preservation process. While each setting provides intelligence for the next in the continuum, Setting 3 (Design Role) epitomizes the hub for processing such intelligences under the creative auspices of design to, in turn, map how the resources should be dealt with in Setting 4.

5.2.3. Recommendations

Firms and workers associated with the settings have the advantage of interpreting and adapting the model to their circumstances. This is important to all, but more so to Setting 3. Here, the accumulated intelligences and design creativity come together in a synthesis process that would shore up the project treatment under consideration. Design firms may find the setting model beneficial for rethinking how to go about the predesign information for preservation design projects. For example, should Settings 1 and 2 information be an in-house responsibility—assuming the availability of resources or should such information obtain with a contractual agreement with specialists in other setting fields?

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BODILY INTERACTIONS IN CULTURAL HERITAGE FOCUSED EXTENDED REALITY STUDIES

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Abstract. Today, Extended Reality (XR) technologies open up new possibilities in the cultural heritage domain by allowing the integration of digital content and new virtual layers onto cultural artifacts, as well as the facilitation of distinct interactive processes. XR environments, which encompass Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), introduce new and intriguing experiences to the heritage field through multisensory and bodily interactions. This study aims to present a comprehensive state of the art regarding bodily interactions in cultural heritage-focused XR studies by reviewing and analyzing the existing literature. To do so, a systematic literature review protocol was adopted to understand how interactive experience is studied in the literature that involves body-related approaches and XR systems in cultural domains. A thorough examination of the literature was conducted using Elsevier's Scopus database, resulting in a dataset of 1063 records processed with VOSviewer. Within this dataset, the keyword co-occurrence analysis identified four cluster groups representing key themes in the literature that are related to bodily interactions in cultural heritage focused XR studies. These clusters were examined in more detail by empirically selecting literature samples. Network, density, and overlay visualizations were also created during the analysis to interpret and represent the results. This study contributes to a better understanding of the role of bodily interactions in XR and heritage studies in promoting cultural heritage preservation and dissemination.

Keywords: *literature review, embodied experience, bodily interaction, extended reality, cultural heritage*

ملخص. تفتح اليوم تقنيات الواقع الممتد (XR) إمكانيات جديدة في مجال التراث الثقافي من خلال السماح بدمج المحتوى الرقمي والطبقات الافتراضية الجديدة في المصنوعات الثقافية، فضلاً عن تسهيل العمليات التفاعلية المتميزة. تقدم بيئات XR، التي تشمل الواقع المعزز (AR)، والواقع الافتراضي (VR)، والواقع المختلط (MR)، تجارب جديدة ومثيرة

للاهتمام إلى مجال التراث من خلال تفاعلات جسدية ومتعددة الحواس. تهدف هذه الدراسة إلى تقديم حالة شاملة من الفن فيما يتعلق بالتفاعلات الجسدية في دراسات XR التي تركز على التراث الثقافي من خلال مراجعة وتحليل الأدبيات الموجودة. وللقيام بذلك، تم اعتماد بروتوكول مراجعة الأدبيات المنهجية لفهم كيفية دراسة التجربة التفاعلية في الأدبيات التي تتضمن الأساليب المتعلقة بالجسم وأنظمة XR في المجالات الثقافية. تم إجراء فحص شامل للأدبيات باستخدام قاعدة بيانات Elsevier's Scopus، مما أدى إلى مجموعة بيانات مكونة من ١٠٦٣ سجلاً تمت معالجتها باستخدام VOSviewer. ضمن مجموعة البيانات هذه، حدد تحليل التواجد المشترك للكلمات الرئيسية أربع مجموعات عنقودية تمثل موضوعات رئيسية في الأدبيات المرتبطة بالتفاعلات الجسدية في دراسات XR التي تركز على التراث الثقافي. تم فحص هذه المجموعات بمزيد من التفصيل عن طريق اختيار عينات الأدب تجريبيا. تم أيضًا إنشاء تصورات الشبكة والكثافة والتراكب أثناء التحليل لتفسير النتائج وتمثيلها. تساهم هذه الدراسة في فهم أفضل لدور التفاعلات الجسدية في XR ودراسات التراث في تعزيز الحفاظ على التراث الثقافي ونشره.

الكلمات المفتاحية: *مراجعة الأدبيات، التجربة المتجسدة، التفاعل الجسدى، الواقع الممتد، التراث الثقافى.*

1. Introduction

Technological advancements throughout history have always influenced the way people think, express themselves, communicate, interact with each other, and experience the world. Extended Reality (XR) in particular, as one of the present technological advancements, appears to have a critical capacity that impacts how we interact, experience, and interpret both in physical and virtual space. XR stands out as a transformational force with the potential to change our connection with cultural heritage, offering distinct benefits and opportunities in comparison to traditional representation methods that we usually encounter in the heritage domain. Here, Extended Reality, involving Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), refers to all environments that bring the virtual information and the physical world together, each in its own distinct way. XR facilitates immersive and interactive experiences, fundamentally altering how individuals connect with and interpret heritage. Today, XR technologies offer new possibilities to the cultural heritage field by enabling the incorporation of digital content and new virtual layers onto cultural artifacts and facilitating distinct interactive mechanisms. Same as how the invention of printed media and broadcasting technologies had an impact on cultural heritage in the past, XR technologies can enhance the preservation and dissemination of heritage knowledge. By improving user experience and engagement, XR can enrich how people understand, appreciate, and connect with cultural artifacts and heritage sites. Furthermore, XR environments introduce unfamiliar spatial layers, intriguing experiences, and exploratory interactions to the heritage field. Interactions in XR tend to be multisensory since they result from the effects of tactile, visual, auditory, olfactory, and gustatory cues in relation to space and media. As the subject interacts with this new reality, manipulates both its actual and virtual objects, perceives and responds to the actions, this new unfamiliar blended space and its materiality keep being re-created and re-interpreted through bodily acts and in-between presences. Hence, it is important to consider such embodied and performative experiences when designing or studying extended realities. From this point of view, this study aims to present a comprehensive state of the art regarding bodily interactions in cultural heritage focused extended reality studies by reviewing and analyzing the literature. In doing so, a systematic literature review protocol was followed to understand how interactive experience is studied in the existing literature that involves body-related approaches and interactive XR systems in cultural domains.

2. Methodology

2.1. SEARCH STRATEGY AND DATA COLLECTION

To begin with, Elsevier's Scopus database was selected as the main digital library to perform the searches. The search strategy was designed to search relevant keyword groups in the title, abstract, and keywords of articles, conference papers, and book chapters written in English before the year 2023. In order to exclude irrelevant subject areas such as Medicine or Biology, subject areas were also limited to Arts and Humanities, Computer Science, Multidisciplinary, and Social Sciences. The relevant keyword combinations were grouped from a general to a more specific scope and used in the creation of advanced search strings. Three different advanced search strings were created in consideration of both keyword groups and search criteria by using Boolean operators. Table 1 shows keyword groups and the total number of results obtained for each search string. As it can be understood from the number of results, each search string was created to narrow the search and focus on the main research issue. The literature that is concerned with bodily interaction/experience and XR contains over 36 thousand results. Without body related keywords, heritage, interaction and XR focused literature gives over 8 thousand results. The literature that is in the concern of our main research issue focuses on the intersection of both bodily interactions, XR experiences and heritage studies. Consequently, the final search resulted in the bibliographic dataset of 1063 records containing citation information, abstract text, author keywords, and index keywords. This data set was then analyzed and interpreted by utilizing the open-source bibliometric analysis tool VOSviewer.

TABLE 1. Keyword groups used in the creation of advanced search strings

OR		**OR**		**OR**			**RESULTS**
extended augmented virtual blended mixed immersive interactive digital technology*	**AND**	interaction experience	**AND**	body bodily body-space body-space-media movement embodied gesture*			36963
extended augmented virtual blended mixed immersive interactive digital technology*	**AND**	interaction experience	**AND**	heritage exhibition gallery museum			8563
extended augmented virtual blended mixed immersive interactive digital technology*	**AND**	interaction experience	**AND**	body bodily body-space body-space-media movement embodied gesture*	**AND**	heritage exhibition gallery museum	**<u>1063</u>**

2.2. DATA ANALYSIS METHOD

VOSviewer is a software tool that is used for creating, visualizing and exploring bibliometric networks in order to analyze the related literature (see Van Eck & Waltman, 2010, 2014). The software enables various advanced bibliometric analyses such as co-authorships, co-citations, co-occurrences, and so on (Van Eck & Waltman, 2023a). As our data analysis method, keyword co-occurrence analysis was adopted since it examines the links between keywords in the literature to understand the knowledge components and knowledge structure of a scientific field (Radhakrishnan et al., 2017). Creating co-occurrence networks involves pinpointing keywords in the textual data, calculating the frequencies and strengths of co-occurrences, and analyzing the networks to identify central keywords and clusters of themes

(Van Eck & Waltman, 2023a). In the study, the RIS file containing title, abstract, and keywords information of 1063 Scopus search results were used in VOSviewer software to execute a keyword co-occurrence analysis with LinLog/modularity normalization method. The minimum number of occurrences of a keyword was set to five. A thesaurus file was manually created and used in the software to clear any duplicates by merging synonymous keywords like museum-museums, AR-augmented reality, and so on. After obtaining clusters of themes from the keyword co-occurrence analysis in VOSviewer, the analysis was detailed and the clusters were examined through literature samples that were empirically selected from the clusters to better understand the results.

3. Results and Discussion

In the keyword co-occurrence analysis, out of 5938 keywords, 225 met the threshold and 4 different cluster groups emerged based on word relations. When examining the relationship between words, publications with identical words in their titles, abstracts, or full texts indicate that they are related. Table 2 shows these cluster groups obtained by the keyword co-occurrence analysis conducted via VOSviewer. Here, four cluster groups reveal the important issues and themes emerging in the literature. To have a further understanding of the analysis, the data set was also reviewed by empirically selecting samples from the clusters based on keywords with the highest impact within each cluster. Three different data visualizations – network visualization based on the occurrence weights of the keywords (Figure 1), density visualization showing heavily focused keywords (Figure 2), and overlay visualization based on yearly trends (Figure 3), were also created during the analysis to interpret and represent the results. These three data visualizations discussed in the study are essential components of the keyword co-occurrence analysis. They collectively reveal crucial details, facilitate effective communication, enrich the interpretation of results, and guide further exploration for the readers. The network visualization provides an intuitive depiction of keyword connections, revealing notable terms and groups within the dataset and assisting in understanding the organization and underlying themes. The density visualization highlights frequently recurring words and assists researchers in identifying key concepts or subjects of importance in the literature. The yearly trend overlay visualization offers a temporal perspective, demonstrating how keyword connections develop over time. This temporal dimension contributes to the identification of developing trends, shifts among academic interests, and the changing prominence of topics.

TABLE 2. Cluster groups and distribution of keywords (in alphabetical order)

Cluster 1 (39)	Cluster 2 (27)	Cluster 3 (32)	Cluster 4 (28)
affordances	3d interactions	3d	dance
augmented reality	cameras	3d computer graphics	digital art
blending	computer simulation	3d modelling	digital technologies
body movements	display devices	3d reconstruction	embodied experience
communication	edutainment	animation	exhibition buildings
computer science	embodied learning	archaeology	exhibition halls
cultural artifacts	entertainment	architectural design	exhibitions
design	eye tracking	architecture	experience design
digital contents	gesture recognition	authenticity	games
education	gesture-based interactions	avatar	human bodies
embodied cognition	gestures	cave	human-computer interactions
embodied interaction	haptics	computer graphics	installation
embodiment	human behavior	cultural heritage	intangible cultural heritage
emotions	interaction	digital heritage	interaction design
experience	interactive display	digital humanities	interactive art
full-body interaction	interactive environments	gamification	interactive installations
gallery	intuitive interaction	head movements	interactive media
head mounted displays	leap motion	heritage sites	interactive systems
identity	multi-modal interactions	historic preservation	mapping
immersive learning	multi-modal interfaces	history	memory
kinect	natural interactions	immersion	multimedia systems
learning	navigation	immersive environments	new media
learning experiences	tangible user interfaces	interactive computer graphics	performance art
mixed reality	touch screens	interactivity	public space
mobile augmented reality	user interaction	motion capture	real time systems
mobile devices	user interface	presence	sensors
movement	virtual objects	real environments	tangible interaction
museums		serious games	walking
perception		virtual environments	
phenomenology		virtual reality	
public displays		virtual worlds	
spatial interaction		visualization	
storytelling			
teaching			
touchless			
tourism			
user experience			
visual communication			
wearable technology			

Cluster 1: museums, AR, user experience, embodiment
Keywords like "museums", "augmented reality", "user experience", and "design" are included in Cluster 1 as they are frequently used together in the literature (see Table 3). This suggests that there is a significant amount of research on the use of Augmented Reality in museums and the importance of designing immersive experiences to increase user engagement. Studies in this cluster focus on the design and UX evaluations of 3D interactive installations, Kinect-based systems, immersive theaters, AR applications usable on tablets, smartphones, etc. in museums (Madsen et al., 2012; Aguilera, 2014; Harrington, 2020). User Experience (UX) studies are insightful for examining not only the technical aspects of the interactive museum installations but also their content, namely what makes the content understandable to people, what are the pedagogical benefits, and how people feel when they are exploring virtual layers (Pietroni et al., 2018). Studies mainly approach UX as the collection of all behaviors, actions and attitudes users have when interacting with an interface; therefore, they can provide guidance in designing interactive systems in museums. For instance, in their study, Barneche-Naya & Hernández-Ibáñez (2019) compares various natural gesture-based interactions in a museum setting by evaluating user experiences through accuracy and completeness of the goals, time spent during tasks, fatigue, comfort, attention, and pleasure. The embodiment part that appeared in this cluster is due to the abundance of studies focusing on Natural User Interface (NUI) designs. The term NUI refers to a group of user interfaces that allow the user to communicate with an interactive system in a way that is similar to how he/she communicates with the physical world – such as using voice, hands, and body. It is emphasized that interacting via natural gestures and other bodily movements stimulates curiosity and embodied involvement in museums (Pietroni et al., 2018). An example of natural interaction can be users moving their arms mimicking a bird flapping to “take off” and perceiving a landscape from a different point of view. In addition to NUIs, immersive aspects of the interactive systems and the importance of narration are highlighted in this cluster. Aguilera (2014) points out how museums with immersive theaters utilizing 3D projection systems can serve as a unified media system that immerses visitors and changes over time between abstract and figurative in degrees of representation. Regarding the importance of narration, studies show that the use of storytelling elements and narration can enhance emotional involvement, learning, and remembering heritage content (Bellucci et al., 2014; Pietroni et al., 2018).

TABLE 3. Top 10 keywords in Cluster 1 (ordered by their occurrence counts)

CL	Keywords	OC	LC	LS
Cluster 1	museums	227	117	849
	augmented reality	114	93	442
	user experience	95	89	388
	design	89	94	339
	embodied interaction	50	60	189
	education	38	62	145
	mixed reality	36	67	174
	embodiment	32	59	129
	kinect	30	47	129
	body movements	27	47	104

Abbreviations: CL=Cluster Legend; OC=Occurrence Count; LC=Links Count; LS=Total Link Strength

Cluster 2: *user interface, gesture recognition, multi-modal interactions*

Keywords like "user interface", "gesture recognition", and "multi-modal interactions" in Cluster 2 prove that there is an interest in exploring different interaction modalities and user interfaces for interactive experiences in cultural heritage (see Table 4). This involves using gesture-based interactions or combining different forms of interaction in order to create more engaging and natural experiences. Many studies focus on the ways to track body movements and technologies for gesture recognition (Agate & Gaglio, 2018; Cafaro et al., 2010; Camurri et al., 2004). This cluster contains studies that aim to design and test user interfaces (UIs) that include different modes of interactions like hand interactions, voice commands, and gaze interactions. While some studies make use of multiple modalities at once (Giariskanis et al., 2022), some others focus on only one interaction. For instance, Calandra et al. (2016) study a NUI that utilizes gaze interactions to navigate 360-degree panoramic artworks presented on wall-sized displays with eye movements. Camurri et al. (2010) make use of a full-body pointing interaction mechanism in which users mimic the use of binoculars with their hands while gazing at installations in order to interact with the system. While UI designs that incorporate gesture-based interactions are at the center of attention (Fanini et al., 2015), not digital interfaces but also tangible interfaces are researched in the literature. Tangible interfaces combine digital elements with tangible objects like small boxes, steering wheels, cylinders, soft touchable fabrics, and other different tactile objects (Martínez-Ruiz et al., 2020; Phichai et al., 2021). Here, users basically interact with the system by physically interacting with tangible objects. However, the term "tangible interaction" refers to a broader area that includes Tangible User Interfaces (TUIs) combining graphical representations, full-body interactions, interactive systems, and gestural input methods (Shaer, 2009). Hornecker and Buur (2006) identify four key themes that require to be addressed when designing or evaluating tangible interactions: *Tangible Manipulation* refers to the materials with tactile characteristics; *Spatial Interaction* indicates the fact that tangible interactions occur in the physical space by bodily movements; *Embodied Facilitation* emphasizes how the arrangement of virtual elements, tactile objects, and physical space influences and directs patterns of use; *Expressive Representation* concentrates on the expressiveness and clarity of the digital and material representations used by tangible interaction systems. Shaer (2009) claims that tangible user interfaces help us focus particularly on the interaction itself and the ways users interact with the system rather than the visible (graphical) interface.

TABLE 4. Top 10 keywords in Cluster 2 (ordered by their occurrence counts)

CL	Keywords	OC	LC	LS
Cluster 2	user interface	108	93	457
	gesture recognition	40	65	176
	interaction	39	62	148
	multi-modal interactions	36	68	164
	gesture-based interactions	34	67	157
	gestures	31	51	143
	natural interactions	30	52	136
	human behavior	25	41	97
	display devices	22	49	98
	eye tracking	22	34	74

Abbreviations: CL=Cluster Legend; OC=Occurrence Count; LC=Links Count; LS=Total Link Strength

Cluster 3: *VR, cultural heritage, digital heritage, historic preservation*
Cluster 3 consists of keywords like "virtual reality", "cultural heritage", and "digital heritage" which imply that there has been research on the use of Virtual Reality technologies to preserve and present cultural heritage (see Table 5). This cluster also includes keywords that are related to visualization, computer graphics, and historic preservation which indicates a multidisciplinary approach in developing immersive and visually rich experiences. Studies in this cluster mainly focus on capturing and preserving the current state of heritage sites and artefacts, documenting and representing tangible and/or intangible heritage values, and creating interactive and immersive experiences of heritage content. Various techniques and methodologies like 3D modelling, texture mapping, photogrammetry, advanced rendering techniques, etc. are adopted in capturing and representing heritage sites and artefacts in Virtual Reality (Wang et al., 2017; Juckette et al., 2018; Cantatore et al., 2020). Various studies aim to preserve and disseminate intangible heritage and historic values by making use of VR environments (Rogers et al., 2018; Skovfoged

et al., 2018; Rodil et al., 2020; Pistola et al., 2021). Schreer et al. (2022) create an interactive documentary of a sensitive historical context like the Holocaust as a VR experience. Serra (2020) focuses on preserving an ancient Egyptian game as an intangible cultural heritage by developing an interactive gaming experience in Virtual Reality. Fu et al. (2020) assert that VR improves users' awareness and knowledge of cultural heritage because users in VR, gain knowledge through their bodily interactions. Regarding bodily interactions and movements, users need navigational ability to a degree when they are immersed in a virtual environment so they can move around and explore the virtual space, just like they could in the physical world. The navigation and interaction in VR environments are usually enabled by using the controllers of head-mounted displays. Here, the challenges of controlling virtual bodies or avatars (if any), navigating in VR space, interacting with virtual objects and access graphical menus by using controllers get addressed in this cluster. Furthermore, various studies aim to go beyond the limits of existing controller interactions by implementing natural gesture recognition in VR environments (Li et al., 2019; Kalarat & Rattanarungrot, 2020). For instance, Kühn et al. (2020) develop and test a gesture alphabet consisting of seven hand gestures that will be recognized by a Kinect camera and then, get translated into real-time VR interactions.

TABLE 5. Top 10 keywords in Cluster 3 (ordered by their occurrence counts)

CL	Keywords	OC	LC	LS
Cluster 3	virtual reality	208	110	834
	cultural heritage	135	93	498
	digital heritage	52	78	199
	visualization	50	75	232
	3d computer graphics	41	65	180
	immersion	38	64	163
	interactive computer graphics	36	59	132
	history	32	61	141
	animation	29	50	107
	historic preservation	28	55	131

Abbreviations: CL=Cluster Legend; OC=Occurrence Count; LC=Links Count; LS=Total Link Strength

Cluster 4: *human-computer interactions, exhibitions, interactive systems, interactive art*

Cluster 4 contains keywords like "human-computer interactions", "exhibitions", and "interactive systems" highlighting the significance of the interaction between humans and technology in creating interactive XR experiences in cultural heritage (see Table 6). This cluster also includes words associated with digital technologies, gaming, and interactive art, indicating a wide range of contexts and applications for interactive experiences in heritage studies. Part of this cluster's studies concentrates on museum and gallery exhibitions that employ interactive art pieces. These also include performance art employing XR technologies and art installations that respond to bodily interactions and movements (Wiethoff & Butz, 2010; Bristow, 2017; Camci & Graeme, 2017; Bomba & Dahlstedt, 2019; Peressini, 2019). Cabrita and Bernardes (2016) develop a framework for human-computer interaction to explore embodied experience in exhibited interactive artworks. To them, interactive art offers an active conversation between the spectator and the surrounding space, facilitated by a computational system. Moreover, the artistic applications of interactive systems tend to eliminate user interfaces. The human body itself can serve as a natural interface when non-invasive tracking methods are incorporated (Cabrita & Bernardes, 2016). Hence, this cluster involves not only research investigating human-computer interactions but also research that seek out qualitative meanings behind body-space-technology interactions and human-machine relationships. Some of the studies in this cluster integrate gaming elements in interactive systems and exhibited content. For instance, Liu et al. (2021), aim to develop XR games that allow users to interact and play around with the heritage context – which increases engagement with the heritage values by enabling various interactions with the artifacts. some studies focus on the design and evaluation of natural user interfaces and interactive systems tracking and responding to body movements in museum installations that interpret cultural heritage. Antal et al. (2016) designed an interactive museum installation in which visitors explore the excavation of the Termae by interacting with virtual objects and environments through natural gestures and bodily movements. Barneche-Naya and Hernández-Ibañez (2021) study different movement schemes in museum installations with natural user interfaces.

TABLE 6. Top 10 keywords in Cluster 4 (ordered by their occurrence counts)

CL	Keywords	OC	LC	LS
Cluster 4	human-computer interactions	169	107	695
	exhibitions	137	102	534
	interactive systems	78	88	344
	interactive art	57	67	202
	digital technologies	54	67	180
	interaction design	37	58	152
	intangible cultural heritage	36	47	130
	games	28	53	105
	real time systems	26	48	88
	performance art	25	43	92

Abbreviations: CL=Cluster Legend; OC=Occurrence Count; LC=Links Count; LS=Total Link Strength

Keyword co-occurrence analysis visualizations

The three different data visualizations mentioned in this research, network visualization (Figure 1), density visualization (Figure 2), and overlay visualization based on yearly trends (Figure 3), were preferred because they provide a complete, intuitive, and dynamic depiction of complicated data, allow for a more in-depth analysis of word connections, notable themes, and trends in time within the data collection. Figure 1 shows the network visualization of the keyword co-occurrence analysis which reveals the relationship between keywords. Each node represents a keyword that co-occurs in the literature at least 5 times. The size of each node reflects the number of occurrences of the keyword. Each color represents a cluster group – there are four separate cluster groups. The links connecting nodes to each other represent the relationship between keywords in the literature. Figure 2 shows the density visualization of the keyword co-occurrence analysis which displays the keywords that are mostly focused in the literature. The literature focusing on bodily interactions in XR and heritage studies then, mainly evolves around the nine interconnected keywords which are *museums*, *virtual reality*, *human-computer interactions*, *exhibitions*, *cultural heritage*, *augmented reality*, *user interface*, *user experience*, and *interactive systems* (see Figure 1 and 2). The results show that bodily interactions in XR and cultural heritage are mainly studied along with gestures, user interfaces, and user experiences. Both network and density visualizations indicate that some keywords appear less in the literature. However, this does not mean that keywords with smaller node or lesser density can be neglected. In order to have a holistic understanding on the literature, the dimension of time needs to be addressed as well. In this regard, Figure 3 shows the overlay visualization of the keyword co-occurrence analysis which reveals the research trends throughout the years via color codes. Here, the keywords *embodied interaction* and *intangible cultural heritage* as the largest yellow nodes indicate that these two keywords are the two main trending keywords used in the literature currently. Similarly, the keywords like *storytelling*, *3D modelling*, *heritage sites*, *gamification*, and *tourism* are in yellow meaning that they appear in the literature after 2018. Yet, the nodes of these keywords are all the smallest in size; therefore, there is lesser research relating these keywords with bodily interactions. Lastly, the keywords *augmented reality* and *user experience* appear to be newer than *virtual reality* and *user interface* which can be interpreted to be a result of the idea of user centered design and technological developments.

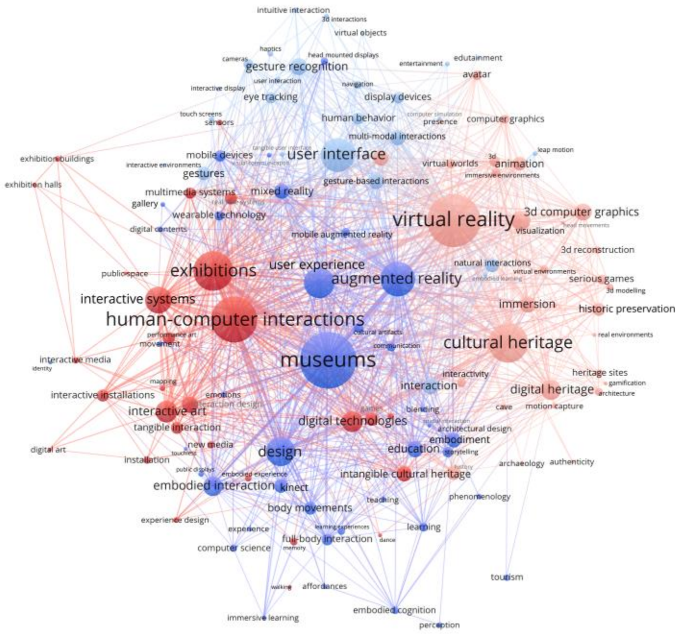

Figure 1. Keyword co-occurrence analysis: **Network visualization**

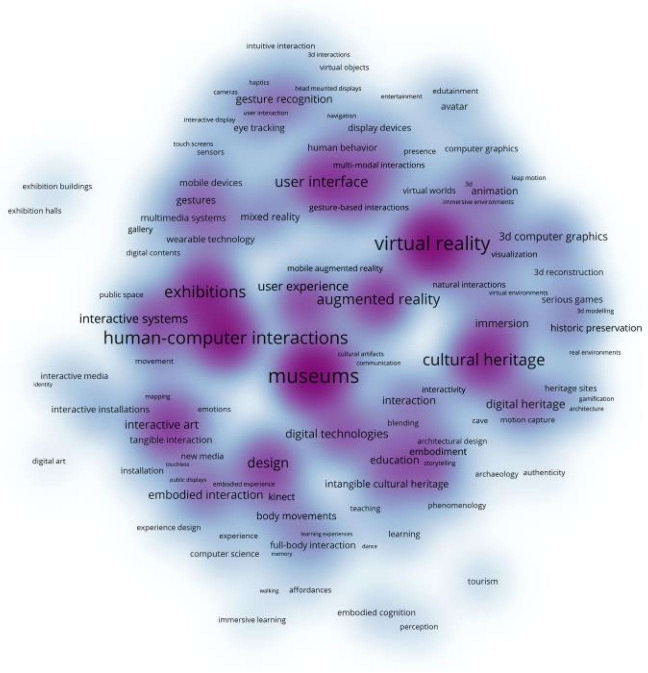

Figure 2. Keyword co-occurrence analysis: **Density visualization**

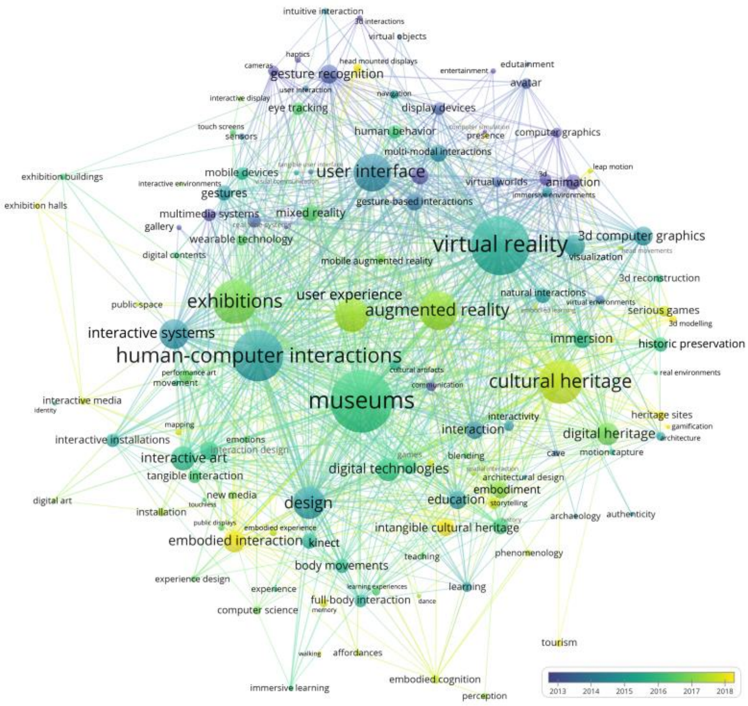

Figure 3. Keyword co-occurrence analysis: **Overlay visualization**

4. Conclusion

The research employed a bibliometric and systematic literature review approach that utilized VOSviewer open-source software in order to analyze and interpret the existing literature. Here, it is important to note that relying solely on keyword co-occurrence analysis may oversimplify complicated relationships in literature as it fails to capture any causal and contextual connections between terms. In the study, this limitation was addressed by incorporating an empirical selection process to include contextual dimensions and causal relationships within the clusters in the analysis. In conclusion, the analysis demonstrated various crucial factors in the design and development of bodily interactions in cultural heritage focused XR studies. The importance of creating immersive and intriguing experiences that effectively engage consumers has emerged as an essential aspect. Natural gestures and embodied involvement were found as key components in generating a sense of presence and bodily interaction. Tangible exploration, spatial interaction, and expressive representation have been identified as important components in developing meaningful and compelling XR experiences. Additionally, the analysis highlighted the significance of computer graphics and visualization in XR systems. Such visual aspects are critical in effectively displaying cultural artifacts and heritage settings in virtual environments, enabling users to explore and engage with them. The use of 3D modeling, storytelling, and gamification approaches in XR experiences was also emphasized as intriguing opportunities to enhance the involvement and educational potential. There is a growing interest in the literature on bodily interactive XR systems in the preservation and dissemination of cultural heritage context. XR can enhance involvement, knowledge, and appreciation of heritage sites and artifacts in cultural domains by enabling multisensory, interactive, and embodied experiences. Hence, further research is needed to advance and broaden bodily interactive XR systems in the context of cultural heritage. In this regard, future studies may explore and address new body-related approaches, different types of natural gestures, interactive XR systems' performative aspects, embodied XR experiences, and their ethical and social impacts on society and individuals. Future research can also build upon the current study by exploring user demographics and delving into the various aspects of XR that contribute to an enriched user experience when interacting with cultural artifacts and heritage sites.

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A DEEP LEARNING-BASED MODEL TO ESTIMATE ARCHITECTURAL ELEMENTS OF CLASSICAL OTTOMAN PERIOD MOSQUES

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Abstract. Deep learning algorithms are widely used in architecture for a variety of purposes such as detecting, analyzing, and classifying building types and architectural elements. This paper particularly focuses on the application of deep learning algorithms in the field of architectural heritage. The aim of this paper is to develop a deep learning-based model for predicting and classifying architectural elements, using Süleymaniye Mosque, a masterpiece by Architect Sinan, as a case study. YOLOv4, a CNN-based object recognition algorithm, is employed to identify three distinctive elements of Süleymaniye Mosque: domes, pendentives, and windows. The process of model development includes data collection and refinement, training and testing, as well as validation through architectural element estimation. The F1 score metric is utilized to objectively evaluate the model's performance. The results indicate that the best F1 score for domes (0.80) is achieved in the 6000th iteration, while for windows, the highest F1 score (0.69) is observed in the 3200th iteration. Regarding the pendentive element, both the 650th and 6000th iterations yield a similar F1 score (0.86) as the highest. This study demonstrates the ability of deep learning to recognize historical building elements that belong to a particular style or era.

Keywords: *deep learning, CNN, object recognition, YOLOv4, classical Ottoman period mosques.*

خلاصة. تستخدم خوارزميات التعلم العميق على نطاق واسع في العمارة لمجموعة متنوعة من الأغراض مثل اكتشاف وتحليل وتصنيف أنواع المباني والعناصر المعمارية. تركز هذه الورقة على تطبيق خوارزميات التعلم العميق في مجال التراث المعماري. الهدف من هذه الورقة هو تطوير نموذج قائم على التعلم العميق للتنبؤ بالعناصر المعمارية وتصنيفها ، باستخدام مسجد السليمانية ، وهو تحفة فنية قام بها المهندس المعماري سنان ، كدراسة حالة. يتم استخدام خوارزمية YOLOv4 ، وهي خوارزمية للتعرف على الأشياء تعتمد على CNN، لتحديد ثلاثة عناصر مميزة لمسجد السليمانية: القباب والمثلثات والنوافذ. تتضمن عملية تطوير النموذج جمع البيانات وصقلها ، والتدريب والاختبار ، وكذلك التحقق من الصحة من خلال تقدير العناصر المعمارية. يتم استخدام مقياس درجة F1 لتقييم أداء النموذج بشكل موضوعي. تشير النتائج إلى أن أفضل نتيجة F1 للقباب (0.80) تم تحقيقها في التكرار 6000 ، بينما بالنسبة للنوافذ ، لوحظت أعلى درجة (0.69) F1 في التكرار 3200. فيما يتعلق بالعنصر المعلق ، ينتج عن كل من التكرار 650 و 6000 درجة F1 مماثلة (0.86) كأعلى درجة. توضح هذه الدراسة قدرة التعلم العميق للتعرف على عناصر البناء التاريخية التي تنتمي إلى نمط أو عصر معين

الكلمات المفتاحية: التعلم العميق ، CNN ، التعرف على الأشياء ، YOLOv4 ، مساجد الفترة العثمانية الكلاسيكية.

1. Introduction

Advances in image processing and object recognition algorithms have enabled computers to learn objects in a human-like manner and recognize the learned objects when they encounter them. Computer object recognition has improved in terms of learning ability and accuracy as a result of developments in deep learning technology. Deep learning approaches such as convolutional neural networks (CNN) mimic human learning and classification skills. CNN analyzes visual input by processing it in hidden layers with images, videos, and simultaneous cameras, transforming the data into information and classifying them (Krizhevsky et al., 2012). Earlier, working with these algorithms required skills such as algorithm literacy, programming language knowledge, and programming abilities. The necessity for certain skills and expertise is decreasing as a result of user friendly coding environments and interfaces. As a result, object recognition algorithms, which were previously employed in other areas, are becoming more common in architecture.

This study mainly focused on the problem of recognizing architectural elements. Süleymaniye Mosque was chosen as a case study as it is one of Architect Sinan's masterpiece. This study proposes a deep learning-based model that employs YOLO v4 as a CNN-based object recognition algorithm to predict the historical architectural elements. To objectively evaluate the success of the predictions, F1 score metric is used.

Following this introduction, the paper continues with the background on deep learning in architecture. Next, the model section presents the phases of data collection and refinement, training of the model, and testing the model for an element estimation task. Based on the execution of the model, numerical results are presented. The key findings, limitations, and future improvements of the study is given in the conclusion section.

2. Deep Learning in Architecture

Deep learning (DL) algorithms can uncover and discover intricate patterns by processing data using various techniques. Developed DL algorithms are widely employed in architecture. These algorithms have become essential tools for aiding and expediting the design processes, generating innovative design alternatives, and creating more efficient and user-centric design solutions.

DL algorithms are extensively utilized to automatically detect, analyze, and classify building types (Ma et al., 2022) and architectural elements (Zou et al., 2023; Llamas et al., 2017) with high accuracy. Several studies have explored diverse topics, including roof recognition from aerial images (Amo-Boateng et al., 2022; Zhang and Aliaga, 2022; Noronha and Nevatia, 2001), exterior and interior wall detection, and analysis of building area, interior layout, and space use (Armeni et al., 2016). The identification of structurally crucial elements, such as columns and beams, is also analyzed to ensure building safety (Santarsiero et al., 2021; Mangalathu and Jeon, 2018). DL research focused on building facades has detected architectural elements like doors, windows, and decorative features, performing aesthetic evaluations through these identified elements (Xu et al., 2022; Aydin et al., 2021). Additionally, DL algorithms detect and analyze design styles, providing inspiration to designers during the design process (Hu, 2021; Yi et al., 2020; Yoshimura et al., 2019; Zhao et al., 2019).

The utilization of DL algorithms to support the renovation of historical monuments is common. These algorithms are valuable for determining the construction period by analyzing images of historical monuments, identifying various types of deterioration (such as stains, mold, and algae growth, etc.) on the monuments (Perez et al., 2019). In this context, it can be said that DL algorithms contribute to the successful classification, preservation, and renovation processes of historical monuments (Croce et al., 2023; Şenkal and Alaçam, 2022; Lamas et al., 2021; Llamas et al., 2017).

Additionally, DL algorithms are used to classify historical buildings and monuments for various purposes. For instance, these algorithms are used to classify monumental structures that have similar functional purposes but are confused due to their structural complexity (Ninawe et al., 2020) or for distinguishing iconic historical buildings and monuments with diverse functional purposes in a specific region (Montoya Obeso et al., 2019; Saini et al., 2017). It also enables the automatic detection of architecturally significant structures in video materials with historical importance (Condorelli et al., 2020).

3. Model

This section outlines the utilized environments, algorithms, and metrics for developing the proposed model. It also elaborates on the data collection and refinement processes, the training and testing phases of the deep learning-based model, as well as the execution of the model. Lastly, this section provides an objective evaluation of the model's outcomes.

3.1. ENVIRONMENTS, ALGORITHMS, AND METRICS

Due to the large amount of data and complex processing techniques, training object recognition models is an intensive process that necessitates the use of powerful computer hardware. The limitations of accessing high-performance computers have been overcome thanks to advances in technology by utilizing cloud technologies. Google Colaboratory (Colab) (URL-1), a cloud-based platform that supports both CPU and GPU, is used in this study. Furthermore, the Python programming language is utilized, which allows for easy data transmission between Colab and Google Drive.

The You Only Look Once (YOLO), proposed by Redmon et al. in 2016, is a real-time object detection algorithm based on Convolutional Neural Networks (CNN) architecture. It addresses object detection as a single regression problem, combining image pixels, bounding box coordinates, and probability classes. In 2017, YOLOv2 was introduced at the Computer Vision and Pattern Recognition Conference, enhancing the algorithm's speed, sensitivity, and accuracy (Redmon and Farhadi, 2017). Subsequently, YOLOv3 was released in April 2018, further improving the algorithm's object detection performance, particularly for complex, small, dense, and overlapping objects (Redmon and Farhadi, 2018). In 2020, YOLOv4 was introduced, significantly enhancing the algorithm's speed and accuracy (Bochkovskiy et al., 2020). Given the advancements in YOLOv4 performance, this algorithm has been chosen for use in this study.

The F1 performance metric calculates the harmonic mean of precision and recall. Precision measures the accuracy of positive predictions, whereas recall measures the capacity to detect positive instances. This score provides a more reliable evaluation, especially in situations where accuracy may be misleading, like in imbalanced data categorization challenges. The F1 score is commonly used to evaluate classification algorithms and to comprehend model performance (Chicco et al., 2020; Chinchor et al., 1993).

3.2. DATA COLLECTION AND REFINEMENT

For the development of the model, the Süleymaniye Mosque was chosen, as it stands as one of the masterpieces built by Architect Sinan and is accessible for visits and documentation through photographs.

The dataset of the study consists of 77 photographs taken by the authors from the interior space of the Süleymaniye Mosque. The captured photographs were in various resolutions. During the dataset preparation process, these resolutions were reorganized and adjusted to a uniform resolution of 416x416 pixels.

As widely recognized elements of Sinan's architectural style, domes, pendentives, and windows have been chosen for the recognition task. These elements in the photos are manually labeled using the LabelImg interface, an open-source image annotation tool (Tzutalin, 2015). The labeling process results in a text file containing the starting coordinates (x and y), width (w) and height (h) information of the bounding box used for labeling in the interface, along with the ID number of the class name assigned to the labeled object.

The labeled object data and the images containing these objects undergo data augmentation. This process involves applying various transformations to the images, including rotations of 45, 90, 135, and 225 degrees, horizontal and vertical reflections, as well as blurring and hue adjustments (see Table 1). Through these operations, the final number of images increased to 770 (600 for training and 170 for testing), with a total of 6880 labeled objects. The distribution of the number of images used in the training, testing, and execution stages of the model is presented in Table 2.

TABLE 1. Data augmentation (Photos by authors).

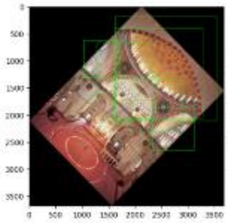
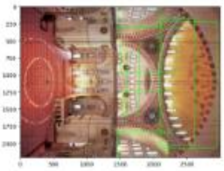
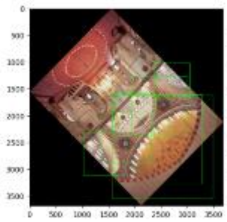
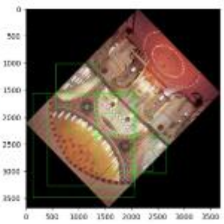
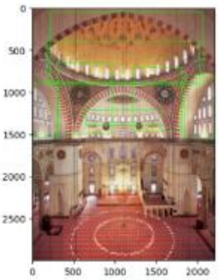
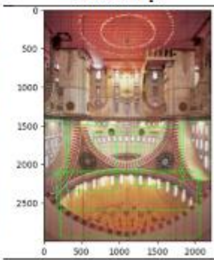
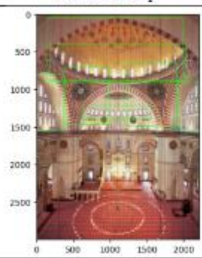
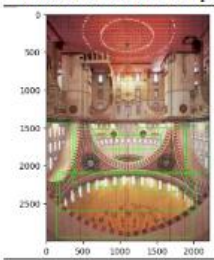
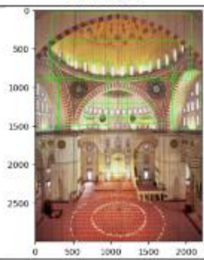
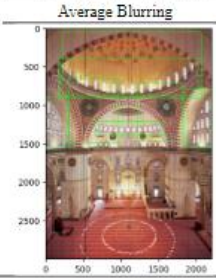
Original	Transformed	
	45° Rotation	90° Rotation
		
	135° Rotation	225° Rotation
		
	Vertical Flip	Horizontal Flip
		
	Horizontal and Vertical Flip	Raise Hue
		
	Average Blurring	
		

TABLE 2. Dataset size and distribution.

	Trainig Data Set		Testing Data Set		Execution Data Set	
	Image	Object	Image	Object	Image	Object
Dome	490	1060	170	470	26	73
Pendentive	580	1470	160	410	26	77
Window	590	2620	170	850	27	117
Undefined					11	25
Sum	600	5150	170	1730	38	267

3.3. TRAINING AND TESTING

Prior to training the datasets saved in Google Drive. The codes for displaying, downloading, and uploading the dataset were processed on Google Colab. The training, testing, and execution stages of the proposed object recognition model utilized the YOLOv4 algorithm, the Python programming language, the OpenCV library, and the Darknet neural network.

The effectiveness of deep learning models can be influenced by several factors, including the dataset's size and quality, the duration of training, parameter tuning for the code functions, and the average loss rate. In this study, the parameters employed in the training and testing processes are as follows: batch size of 64, subdivisions of 16, image size of 416x416 pixels, momentum of 0.949, decay of 0.0005, learning rate of 0.001, maximum batches set at 6000, and 24 filters.

The training and testing took a total of 78 hours, conducted at different time intervals using the aforementioned parameters, and were manually terminated. Throughout the process, changes in average loss values and average weight values were monitored and automatically recorded every 50 iterations. These values were used to evaluate the progress of the proposed model at different iteration points.

3.4. ESTIMATION OF ARCHITECTURAL ELEMENTS

The proposed model was validated using 38 photographs. These photographs exhibit the following characteristics:

1. 19 of them are interior photographs of the Süleymaniye Mosque (not included in dataset for training or testing) and contain objects from at least one of the three instructed classes (Figure 1).
2. 12 of them are interior photos of different mosques, with only 9 containing objects from at least one of the three

instructed classes. 3 of these images do not contain any instructed objects (Figure 2).

3. 7 of them contain completely different objects, such as cats, dogs, people, and cars.

For the architectural element estimation task, each photo was uploaded to the model, which then analyzed the photo. When the model detected an architectural element, it annotated the object with a frame and add a text including percentile estimate indicating the probable class to which the detected object belonged. All these operations were performed sequentially for the three selected iterations (650th, 3200th, 6000th) and the estimation percentage of the model were documented.

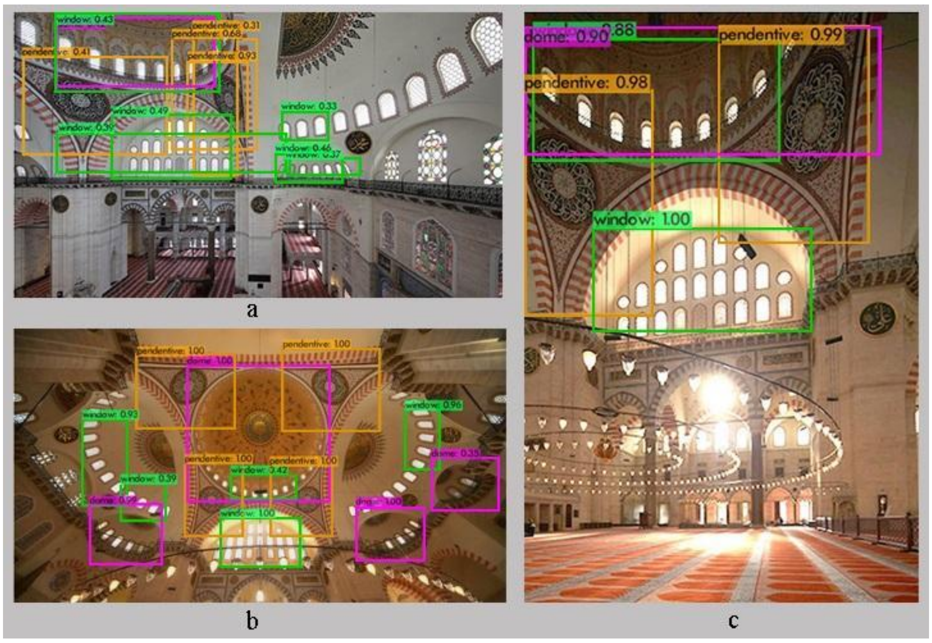


Figure 1. Estimation results of (a) 650th, (b) 3200th and (c) 6000th iterations for reserved Süleymaniye Mosque photographs (Photos by authors).

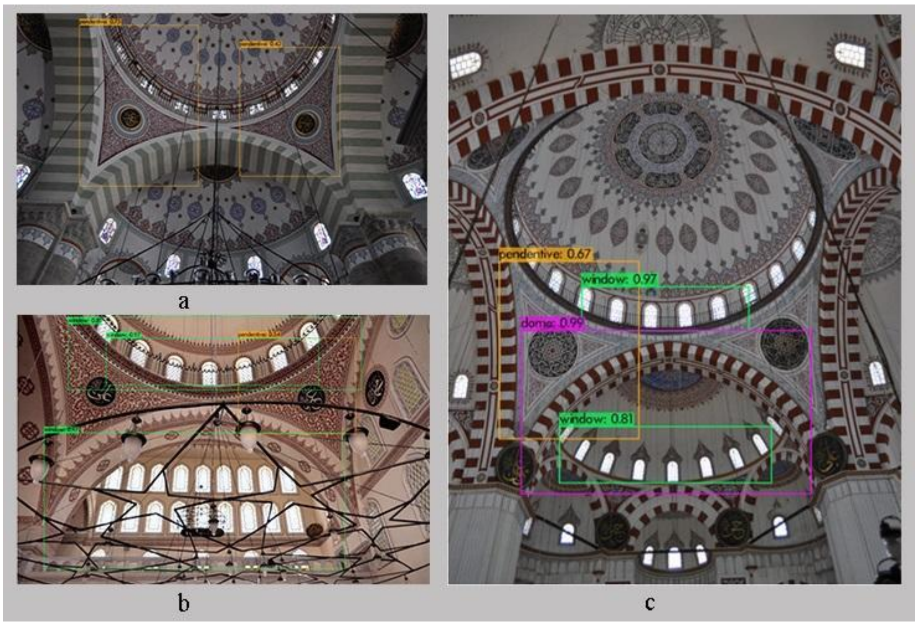


Figure 2. Estimation results of (a) 650th, (b) 3200th and (c) 6000th iterations for other mosque photographs (Photos by authors).

4. Results and Findings

In this section, the model's estimations from three iterations are presented separately for the dome, pendentive, and window elements, following the confusion matrix method (Visa et al., 2011; Townsend, 1971). The confusion matrix allows users to examine the model's prediction performance in four categories:

1. True Positive (TP): The model successfully predicted a positive class.
2. True Negative (TN): The model successfully predicted a negative class.
3. False Positive (FP): The model predicted a positive class when the actual class was negative. Also known as a "Type I error."
4. False Negative (FN): The model predicted a negative class when the actual class was positive. Also known as a "Type II error."

Here positive class refers to the object that the model is trying to detect, while negative class is the complementary category to the positive class. The

F1 score value obtained from precision and recall measures, calculated based on the confusion matrix method (Visa et al., 2011; Townsend, 1971). These estimations and evaluations are elaborated upon in Tables 3. Based on the numerical values provided in Tables 3, the precision, recall, and F1 score values for the dome, pendentive, and window elements have been compiled and are presented in Table 4, 5, and 6 respectively.

TABLE 3. (a)The 650th, (b) the 3200th, (c) 6000th iteration results.

Dome	(+)	(-)
	True Positive	False Negative
(+)	45	28
	False Positive	True Negative
(-)	3	25

Pendentive	(+)	(-)
	True Positive	False Negative
(+)	60	19
	False Positive	True Negative
(-)	0	23

Window	(+)	(-)
	True Positive	False Negative
(+)	25	93
	False Positive	True Negative
(-)	0	24

a

Dome	(+)	(-)
	True Positive	False Negative
(+)	44	29
	False Positive	True Negative
(-)	0	25

Pendentive	(+)	(-)
	True Positive	False Negative
(+)	58	21
	False Positive	True Negative
(-)	1	23

Window	(+)	(-)
	True Positive	False Negative
(+)	63	55
	False Positive	True Negative
(-)	2	24

b

Dome	(+)	(-)
	True Positive	False Negative
(+)	49	24
	False Positive	True Negative
(-)	0	25

Pendentive	(+)	(-)
	True Positive	False Negative
(+)	60	19
	False Positive	True Negative
(-)	1	24

Window	(+)	(-)
	True Positive	False Negative
(+)	58	60
	False Positive	True Negative
(-)	0	25

c

TABLE 4. The 650th iteration results.

	Precision	Recall	F1 Score
Dome	0,94	0,62	0,74
Pendentive	1,00	0,76	0,86
Window	1,00	0,21	0,35

TABLE 5. The 3200th iteration results.

	Precision	Recall	F1 Score
Dome	1,00	0,60	0,75
Pendentive	0,98	0,73	0,84
Window	0,97	0,53	0,69

TABLE 6. The 6000th iteration results.

	Precision	Recall	F1 Score
Dome	1,00	0,67	0,80
Pendentive	0,98	0,76	0,86
Window	1,00	0,49	0,66

5. Conclusion

In this study, the performance of a deep learning-based object detection model, based on the YOLOv4 algorithm, was evaluated on 38 different images across the 650th, 3200th, and 6000th iterations. At the beginning of the training process, the average loss value was approximately 24. However, this value decreased to 22.22, 0.8, and 2.8 in the 650th, 3200th, and 6000th iterations, respectively. Upon examining the results from these three iterations, the lowest precision value was observed for the dome object in the 650th iteration (Table 4), while this value reached 1.00 in the 6000th iteration (Table 6). The highest recall value was achieved for the pendentive object in the 650th and 6000th iterations, while the lowest value was for the window object in the 650th iteration. The highest F1 score was recorded for the dome and pendentive objects in the 6000th iteration, and for the window object, it was in the 3200th iteration. Additionally, the pendentive object also obtained the highest F1 score in the 650th iteration. Furthermore, in the 650th iteration, it was observed that the model's estimations for an object were repeated across different percentage thresholds. In the 3200th iteration, this repetition occurred only once, while in the 6000th iteration, no repeated estimations were observed. In this context, the number of estimations containing lower percentage thresholds (e.g. 30%) is higher compared to the lower percentage estimations in the other three iterations (Figure 1).

Additionally, despite the window object having a higher frequency in the train, test, and execution datasets, its F1 score remains lower across all three iterations (Table 1; Table 3). This observation could potentially arise from the lower image resolution and clarity (not blurred) of the window object within the dataset.

Furthermore, the model tends to make fewer predictions for unidentified class objects across all three iterations. Moreover, in the Süleymaniye Mosque, accurate predictions are most prevalent, with the dome object achieving the highest accuracy during the 6000th iteration, and the pendentive and window objects performing optimally during the 3200th iteration (Figure 1). For the photographs of interior spaces of different mosques, the dome and pendentive objects are best detected during the 6000th iteration, whereas the window object is most effectively identified during the 3200th iteration (Figure 2).

By achieving a more balanced dataset quantitatively and qualitatively for the three objects, such as accounting for variations in brightness and addressing instances where objects are numerous but lack clarity, it is expected that the model's performance in predicting these three objects can be enhanced. The limitations of this study lie in the challenges of creating a larger and more diverse dataset. Having a larger, more varied, and higher quality dataset could potentially enhance the model's estimation capabilities.

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4.A.

DIGITAL MEDIA AND GENERATIVE ART

DIGITAL DESIGN IN AFRICA

A Statistical Overview of Trend and Motivation in the African Continent

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Abstract. The Architecture, Engineering, and Construction (A.E.C.) industry has recently witnessed various innovations, notably integrating Digital Design (D.D.) processes in the industry's workflow. Unfortunately, Africa has been excluded from exploring this development due to its perception as a developing region still reliant on traditional construction methods. This review aims to investigate the trend of Digital Construction (D.C.) in Africa by categorizing several projects based on several data points, including project period, typology, scale, curvature type, and location. A statistical overview of the data will provide a quantitative understanding of D.C. projects in the continent. Furthermore, the study will conduct a literature-based comparative analysis between D.C. projects in Africa. Finally, the review will focus on a select few case studies for in-depth analysis. The expected outcome of this analysis is a comprehensive understanding of the trend and motivation behind D.C. in Africa.

Keywords: *Africa, Digital Construction, Digital Design, Digital Fabrication*

ملخص: شهد مجال العمارة والبناء والتشييد مؤخرا العديد من الابتكارات من ضمنها تطبيقات التصميم الرقمي في تنظيم الأعمال بمشاريع البناء. ولسوء الحظ فإن قارة أفريقيا مستبعدة من تلك التطورات؛ بسبب اعتبارها منطقة نامية لا تزال تعتمد على طرق البناء التقليدى. يهدف هذا البحث إلى تحرى اتجاه البناء الرقمى فى أفريقيا من خلال تصنيف مجموعة من المشروعات بناء على عدة نقاط وهى: موقع المشروع وفترة إعداده وتصنيفه ومقياسه ونوع الإنحناء فى التشكيل المعمارى. وستقوم اللمحة الإحصائية لهذه البيانات بتوفير فهم كمى لمشاريع البناء الرقمى داخل القارة. علاوة على ذلك، تجرى الدراسة تحليلاً

مقارناً - قائما على الأدبيات - ما بين مشاريع البناء الرقمى داخل القارة. وأخيراً تركز هذه الدراسة على استعراض مجموعة مختاره من دراسات الحالة لإجراء تحليل متعمق. والنتيجة المتوقعة من هذا التحليل هو الفهم الشامل لاتجاه التصميم الرقمي في قارة افريقيا والدوافع وراء استخدامه في بعض المشاريع.

الكلمات المفتاحية: *أفريقيا ، البناء الرقمي ، التصنيع الرقمي*

1. Introduction

Design, Construction, infrastructure, real estate and other disciplines have been affected by digitalization, innovative technologies, and new materials. Additionally, new construction techniques have leveraged our build environment to be more comfortable, affordable, safe, sustainable and efficient. (Casini, 2016). The aforementioned factors make the Architecture, Engineering and Construction sector in Africa (ACE) grow interest in the adoption of digital construction technologies and approaches. And despite the countless technologies promising answers to age-old issues of conveying projects on-time, within budget, and to customers' determinations. The adoption process in Africa still hasn't reached full or satisfying implementation of these technologies and approaches. (Oke et al., 2018).

Building information modeling (BIM), 3D printing, robotics, and virtual and augmented reality (VR/AR) are the reflection of digitalization on construction industry which has shown a great benefit to the industry improving the quality of construction, the design process, the sustainability and the safety aspect. BIM is used to design, construct, and operate buildings and infrastructure more efficiently and effectively. It allows architects, engineers, contractors, and owners to work collaboratively throughout the entire lifecycle of a project. (Abdalla & Eltayeb). 3D printing is a method of creating three-dimensional objects by depositing successive layers of material until the desired shape is achieved. In construction, 3D printing can be used to create complex shapes and structures with high precision and accuracy. (Rouhana et al., 2014). Also, robotics plays an important role in improving the productivity and quality of construction projects, especially for complex structures. It can also increase the productivity by reducing the cost and time required for complex structures, as well as creating new design possibilities and improving the environmental performance of buildings. (García de Soto et al., 2018). Virtual Reality (VR) refers to a computer-generated simulation of a three-dimensional environment that can be interacted with using specialized hardware, often involving a head-mounted display (HMD) and controllers. Augmented Reality (AR), on the other hand, involves overlaying digital information, such as images, sounds, or other data, onto the user's view of the real world. Unlike VR, AR does not replace the real environment entirely; it enhances it by adding virtual elements. (Machala et al., 2022)

According to Halim (2010) there is no profession that can effectively succeed in solving its 21st century development challenges unless the professional visions, aspiration, mission and strategies are fundamentally anchored in the realm of knowledge creation and strategically driven by technology. Using the guide of digital and collaboration technology the construction businesses around the world has turned out to be less intricate, projects being done on time, profitability expanding, better nature of work and more customers' satisfaction is being attained (Van Leeuwen, 2003)

The rapid advancement of digitalization techniques has made it easier to construct what considered challenging or unattainable using traditional methods, it revolutionized the field of design and construction, particularly in the realm of complex shapes and surfaces, single and double curved surfaces are easier to conceptualize, design, and realize.

Single Curved Surface – Among the two curves defining the surface, only one exhibits curvature, rendering it developable (mathematically, a developable surface possesses zero Gaussian curvature, allowing it to be flattened onto a plane without distortion). Double Curved Surface – A surface that cannot be flattened without distortion. In the case of a saddle shell, compressive stresses occur along the convex curvature, while tensile stresses emerge along the concave curvature. In the instance of a dome curving uniformly in the same direction, such as the second dome example, the entire structure is under compression (Olgavoisnis, 2019). Among the various projects in Africa that were implemented with the new technologies whether in design or construction process. We concentrated on 200 buildings distributed randomly among the continent and were as either single curved surface (developable) or double curved surface (non-developable).

2. Literature Review

In order to gather and evaluate relevant research studies, a systematic review was carried out in two stages using specific selection criteria. The review focused on the use of digital technology in the construction industry, particularly in Africa, with an emphasis on double curved and curvilinear structures such as towers and stadiums. To conduct the search, four academic publication databases, namely Google Scholar, ResearchGate, ScienceDirect, and Scopus, were utilized. The search yielded a total of 200 published papers in the form of conference papers and journals. The number of papers was later refined based on their titles and abstracts, resulting in a selection of thirty-three papers that met the criteria of interest.

2.1. DIGITAL TECHNOLOGIES IN CONSTRCUTION

Digital technologies (DTs) refer to the use of modern technologies to convert analog information into digital forms, resulting in improved performance capabilities, as stated by (Ezeokoli et al., 2016). In addition, DTs involve the integration of various innovative tools and software applications throughout all stages of a construction project, from conception to completion, as highlighted by (Ikuabe et al., 2022). (Westerman et al., 2011) also defines DTs as the adoption and deployment of technological tools to significantly enhance business performance.

The construction industry around the world is currently undergoing a rapid transformation through the application of digital technologies, which have the potential to enhance efficiency, reduce costs, and improve safety. This literature review aims to present an overview of the current state of digital construction practices in Africa and identify the opportunities and challenges associated with their adoption. On the one hand, several studies have highlighted the challenges facing the construction industry in developing countries with regards to the adoption of digital technologies. For instance, a study by (Oke et al., 2023) noted that many developing countries, including those in Africa, are still struggling to fully embrace digital transformation in their construction sectors. The study further revealed that there are significant barriers to the adoption of digital technologies, including a lack of awareness and understanding of the potential benefits, limited access to technology and infrastructure, Data security and data protection, legal and contractual uncertainties and resistance to change. To better understand these factors, the authors conducted factor analysis, which revealed five clusters of barriers categorized as organizational, management, technical, regulatory, and economic.

2.2. DIGITAL CONSTRCUTION IN AFRICA

On the other hand, a number of studies have highlighted the utilization of digital technology across Africa using digital technology whether in design or construction phase. For example, the Mapungubwe Interpretive Centre situated in South Africa employed digital models to effectively convert advanced geometrical concepts into simple guides construction. This endeavor encompassed the utilization of a mix of commercially accessible computer-aided design (CAD) software (Rhinoceros).

Castagnino et al. (2016) provided a demonstration of digital technologies during the construction phase of a notably intricate infrastructure venture, the Cross-rail project. Noteworthy employment of drones transpired during the physical construction process, facilitating inspections and surveys of the construction site. Advancements in three-dimensional printing were leveraged to prefabricate certain materials, while tasks involving material and inventory assessments were executed through radio frequency identification (RFID) and GPS tracking mechanisms. Furthermore, the project also integrated the deployment of robots and self-directed vehicles.

2.3. 3D PRINTING IN SOUTH AFRICA

South Africa's progress regarding 3DP in construction has benefited from the governmental support from the Rapid Product Development Association of South Africa (RAPDASA), which commissioned a roadmap in 2013 entitled "South African Additive Manufacturing Technology Roadmap" (Raji 2017). As a result, 3DP was used to enhance productivity and efficiency and produce parts for conventional manufacturing. Currently, South Africa is considered globally competitive in polymer-based and metal-based Additive Manufacturing. In Kenya, universities play a keyrole in the current development of digital fabrication, namely 3DP. The African Centre of Technology Studies (ACTS), has collaborated with Kenyatta University (KU) to establish a 3DP technology center aiming to advance 3D Printing for industrial capacity building and IT development (Kolade et al. 2022). This network can boost Africa's economic growth and 3DP adoption (Demissie 2017). In Malawi, the UK-based CDC Group and Lafarge Holcim created a joint venture named 14Trees to improve sustainable building solutions. This project introduces 3DP technology to produce sustainable building infrastructures through 3DP extrusion (Thawer 2021). This project has already produced a 3D printed house and a school and plans to expand to other African countries, including Kenya and Zimbabwe. The 3D printed school in Malawi took 18 h to build and has been functional since June 2021. In 2019, the city of Benguerir in Morocco hosted the first edition of the "Solar Decathlon Africa" to promote renewable energy in the construction industry. In this event, the "Be More 3D" start-up company built a 3D printed house with 32 m2 in less than 12 h. This achievement allows it to get a prize for the most innovative startup, awarded by Green Africa Innovation Booster of IRESEN, the Morocco Research Institute (Mélanie 2019).

However, (Dall'omo, 2017) in a report on digitalization maturity in Africa discovered that South Africa, in general, has an "established" maturity level. The country has a reliable digital adoption level, but with significant room for improvement when compared to the international benchmark in the areas of consistent and affordable internet access, and the provision of digital training and skills.

2.4. DIGITAL CONSTRUCTION AND CURVED ARCHITECTURE

In the paper "Evolution of Nature-inspired Lines in Architecture; an Overview of 20th Century Curvilinear Structural Design Approach Under the Lights of Organic Architecture," the authors appear to have overlooked the existence of curved architecture in Africa, both past and present. Despite the fact that there are numerous buildings on the continent with curved surfaces and roofs, the paper only mentions the work of a few well-known architects such as Gaudi, Fuller, and Wright. This lack of recognition for African architects and their work demonstrates a clear bias towards Western architecture and a disregard for the contributions made by other cultures. To address this issue, further research is needed to highlight the impressive and innovative work being done by African architects. By showcasing examples of curved architecture from across the continent, researchers can help to dispel the notion that this style of design is limited to specific regions or architects.

3. Research Gap

The omission of African architecture from discussions of curvilinear design in the paper "Evolution of Nature-inspired Lines in Architecture" highlights a larger issue of cultural bias within the field of architecture. By acknowledging and celebrating the diversity of architectural styles and traditions from around the world, we can foster a more inclusive and equitable approach to design.

Through interviews conducted with design companies and architects, valuable insights were obtained regarding the existing labor capabilities and digital fabrication techniques in Africa. This research seeks to contribute to the limited literature available on modern African architecture by examining the advancements and potential of digital construction in this specific domain. The purpose of those interviews is to explore the extent to which digital construction methods have been embraced in modern African architecture, focusing on their utilization for single and double curved surfaces.

By conducting interviews with design companies and architects, key information regarding labor effectiveness and the presence of digital fabrication techniques in Africa was gathered.

4. Research Aims

The primary objective of this research is to investigate the trend of Digital Construction (D.C.) in Africa. The study aims to achieve the following research aims:

1. The research aims to categorize 200 construction projects in Africa based on various data points, including curvature or surface type, project duration, typology, scale, digital workflow, materials, digital fabrication technologies employed, data availability, and location. By systematically organizing the projects into these categories, the study seeks to provide a comprehensive and structured overview of the adoption and implementation of Digital Construction practices on developable and non-developable surfaces across the continent.

2.Through the research findings, the study aims to inform industry professionals, researchers, and other stakeholders about the current status and trends of Digital Construction in Africa. By providing quantitative and qualitative data, the research aims to contribute to evidence-based decision-making and strategic planning for the advancement of Digital Construction practices in the continent.

By addressing these research aims, this study aims to shed light on the trajectory of Digital Construction in Africa, offering valuable insights for researchers, and policymakers in the construction industry. 5. Research Methodology

The study utilized a mixed methods approach, combining desk research, email questionnaires, and data analysis techniques to investigate the adoption and implementation of digital fabrication in construction projects in Africa.

5. Research Methodology

The study of the implementation of Digital Construction practices on developable and non-developable surfaces across the continent, utilized a mixed methods approach, combining desk research, email questionnaires sent via email to architects and contractors and researchers involved to gather detailed information about the projects, and data analysis techniques to investigate the adoption and implementation of digital fabrication in construction projects in Africa.

5.1. RESEARCH DESIGN

The research design incorporated both qualitative and quantitative methods to gather comprehensive data on digital construction practices in

Africa. It involved a multifaceted approach, including desk research, email questionnaires, unrecorded informal interviews and data analysis to achieve the research objectives, which aimed at uncovering insights into the adoption, challenges, and successes of digital fabrication in construction projects.

5.2. PARTICIPANTS AND SAMPLE

A purposive sampling strategy was employed to select participants from relevant stakeholder groups in the African construction industry. The sample included construction companies, architects, engineers, and researchers. Participants were selected based on their involvement in digital construction projects in Africa.

5.3. DATA COLLECTION METHOD

5.3.1 Comprehensive Internet Searches

5.3.1.1 Thorough Internet Searches. We conducted comprehensive internet searches. This involved using various search engines, databases, and online resources to identify and locate information related to construction projects in Africa that had integrated digital fabrication into their processes.

5.3.1.2 Identifying Relevant Data Sources. During these internet searches, we identified a wide range of data sources. These sources likely included official reports, academic publications, books, news articles, project websites, and any other publicly available materials that provided insights into the selected construction projects.

5.3.1.3 Variety of Data Sources We sought data from a variety of sources to cross-verify information and provides a more comprehensive view.

5.3.2 Questionnaires were designed and sent via email to architects and contractors involved in the selected projects. The questionnaires aimed to gather detailed information about the projects, such as duration, cost, materials, construction methods, digital workflows, and software used.

5.3.3 Existing research papers and academic literature related to digital construction in Africa were reviewed to gain insights into best practices, and industry trends. These sources provided a theoretical foundation and supported the analysis of the collected data.5.4. Data Classification and Coding

The collected data, including project documentation, questionnaire responses, and research papers, were organized and classified into categories based on relevant themes and variables. These categories include surface type, project location, project type, duration, scale, material used, construction method, digital fabrication technologies used, software used, construction company, and architects. The data were then coded systematically to facilitate analysis and comparison.

5.4. DATA CLASSIFICATION AND CODING

The collected data, including project documentation, questionnaire responses, and research papers, were organized and classified into categories based on relevant themes and variables. Microsoft Excel was the primary tool used for this purpose. The data were categorized into various key themes and variables, including:

- surface type (developable or non-developable)
- project location in Africa (e.g., northern Africa southern Africa, western, Africa, eastern Africa)
- project type (e.g., shell structure, tower, museum)
- Building height (e.g., low rise: less than or equal 4 floors, mid-rise: 5 floors to 12 floors, high rise: 5 floors to 12 floors or skyscraper: over 40 floors)
- duration in years
- scale (e.g., Cultural Architecture, residential)
- material used
- digital fabrication technologies employed (e.g., 3D printing, laser cutting, CNC, robotics fabrication, or laser scanning)
- digital workflow (CAD software)
- responsible construction company and architects and their locations (e.g., International, Regional, or Local firms)

This systematic coding process was instrumental in preparing the data for comprehensive analysis and meaningful comparisons.

5.5. DATA ANALYSIS

5.5.1 Quantitative Analysis: Quantitative data from the questionnaires, such as project durations, costs, and software usage… etc, were analyzed using descriptive statistics. Charts, graphs, and tables were generated to present the findings.

5.5.2 Qualitative Analysis: Qualitative data from the questionnaires, project documentation, and research papers were analyzed in thematic summaries, and clear points to highlight key findings, challenges, and successes in the digital construction landscape in Africa.

5.6. DATA PRESENTATION

The results of the analysis were presented in a clear and organized manner. Quantitative findings were presented using charts, graphs, and tables, highlighting statistical trends and key metrics. Qualitative findings were summarized in the form of clear points and paragraphs. The data presentation aimed to effectively communicate the research findings and support the research objectives.

5.7. LIMITATIONS

Several limitations should be acknowledged. Firstly, the reliance on desk research and self-reporting through questionnaires may introduce potential limitations in data accuracy. Secondly, the availability and accessibility of project data and participant responses may vary.

6. Results

Africa was divided into five regions, that have been researched in detail to calculate the total number of projects that are distinguished with developable and non-developable surfaces. After a process of filtration, it became apparent that there are 197 projects among them 92 projects with developable surface and 105 projects with non-developable surface as shown in Figure 1 (Left). 27.9 % of the projects are concentrated in the northern region, while 25.4 % of the projects are concentrated in the western region and 19.9 % of the projects are concentrated in the southern region. Furthermore, in the continent's eastern region, there are 15.9 % of the projects and in the middle of the continent, there are 10.9 % of the projects as shown in Figure 1 (Right).

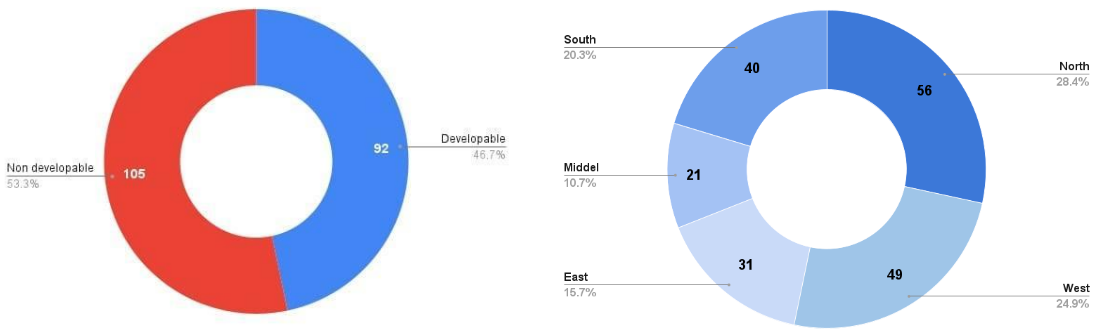


Figure 1. Left: Percentage of projects with developable and non-developable surfaces in Africa, Right: Number of projects in each region of Africa.

The northern region of the continent encompasses Egypt that has 26 projects, followed by Morocco with 12 projects, Algeria with 8 projects, Tunisia with 6 projects and Sudan with 4 projects as shown in Figure 2 (Left), while the western region encompasses Senegal that has 11 projects, followed by Angola with 8 projects, Nigeria with 7 projects, cote d'Ivoire with 5 projects, and both Guinea and Ghana has 4 projects for each. Togo, Niger, and Benin each has 2 projects, and finally, Gambia, Burkina Fuso, Mali, and Sierra Leone each has only 1 project as shown in Figure 2 (Right).

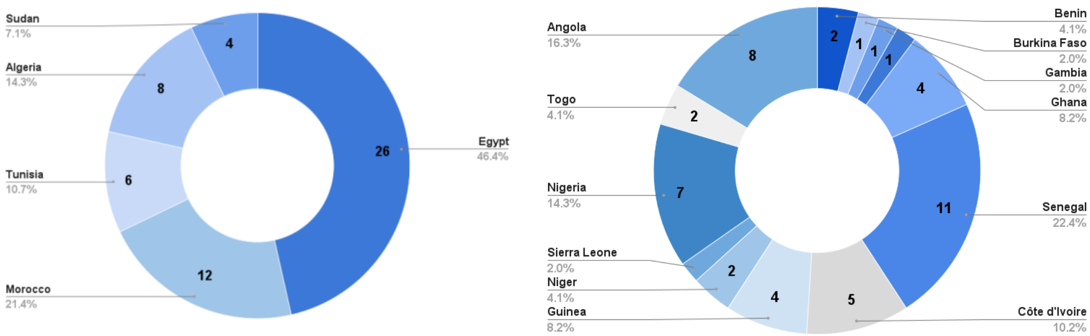


Figure 2. Left: Percentage of projects in the northern region of Africa, Right: Percentage of projects in the western region of Africa.

The eastern region of Africa encompasses Kenya that has 8 projects, followed by Rwanda with 6 projects, Ethiopia with 5 projects, Guinea and Ghana has 3 projects for each, and finally, Mozambique, Malawi, and Mauritius each has only 2 projects as shown in Figure 3 (Left), while the Middle region encompasses Congo that has 6 projects, followed by both Cameroon and Gabon with 5 projects for each, Tanzania with 2 projects, and finally, Central Africa, Chad, and Equatorial Guinea each has only 1 project as shown in Figure 3 (Right). As for the southern region of Africa, South Africa has 26 projects, followed by Zambia with 4 projects, Zimbabwe with 3 projects, Namibia and Botswana has 2 projects for each, and finally, Lesotho, Eswatini, and Comoros each has only 2 projects as shown in Figure 3 (Bottom).

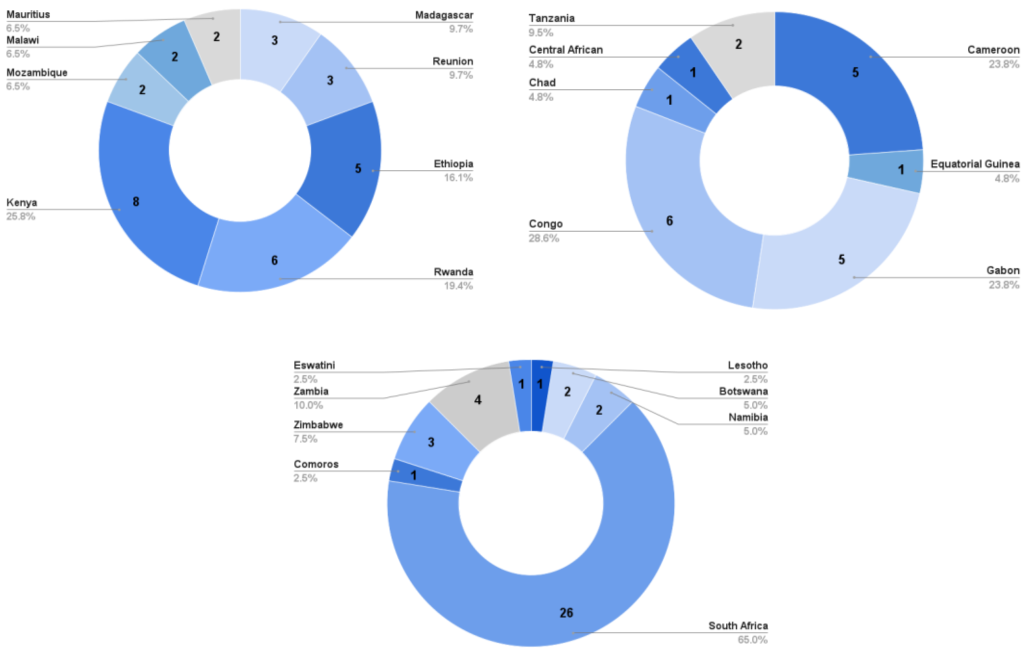


Figure 3. Left: Percentage of projects in the eastern region of Africa, Right: Percentage of projects in the Middle region of Africa, Bottom: Percentage of projects in the southern region of Africa.

It became apparent via an analysis of the projects located in various countries of the African continent that the majority of projects built there are characterized with non-developable surfaces while the minority are characterized with developable surfaces, noting that some countries such as Somalia, Eritrea, and Burundi have no projects, as shown in Figure 4.

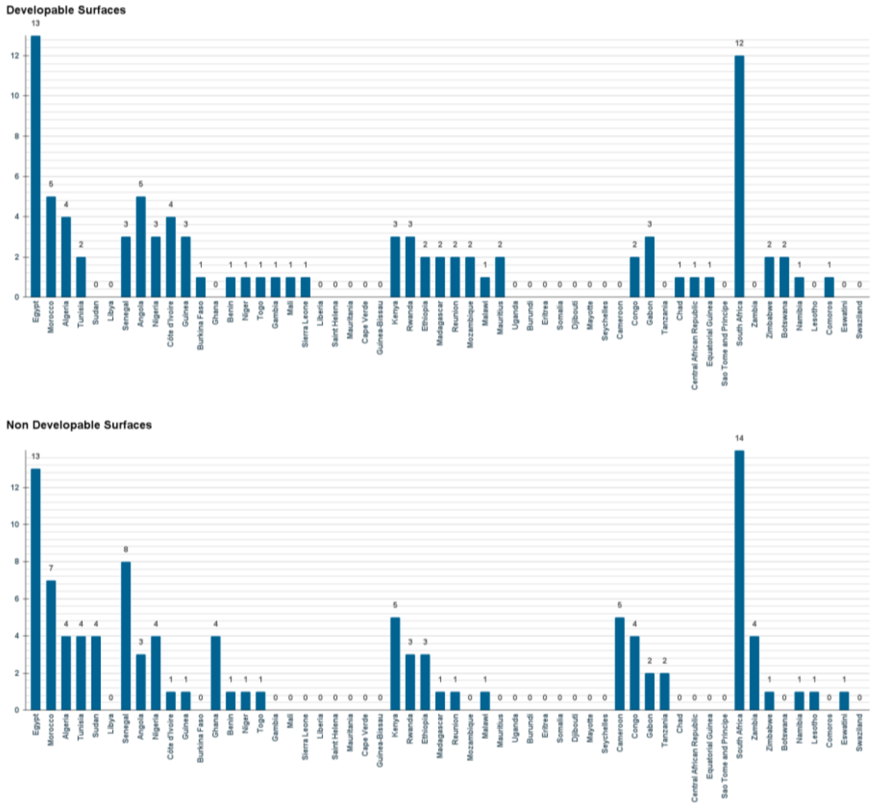


Figure 4. Top: Number of projects characterized with developable surfaces in Africa, Bottom: Number of projects characterized with non-developable surfaces in Africa.

In terms of building category as shown in Figure 5, 20.8% of the projects fall under the category of sports architecture, 18.3% under cultural architecture, 16.8% under public architecture, and 13.2% under commercial and office architecture. With a total of 2.5% and 2%, respectively, the residential and healthcare category has the lowest percentage of projects.

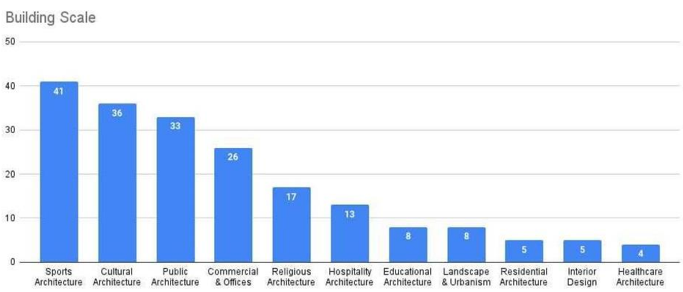


Figure 5. Number of projects in each country in Africa in terms of building scale.

As for project types, as shown in Figure 6, it is apparent that stadia are the most executed projects with developable and non-developable surfaces in Africa as 20.8% of projects were spotted belonging to this category. Coming in second place is airports with 10.7% of projects. Then the third place is occupied by office buildings with 9.1% of projects, followed by hotels and churches each with 6.1% of projects. The mosques, hospitals, and libraries are the less executed projects with developable and non-developable surfaces, with 2.5%, 1.5% and 0.5% of projects, respectively.

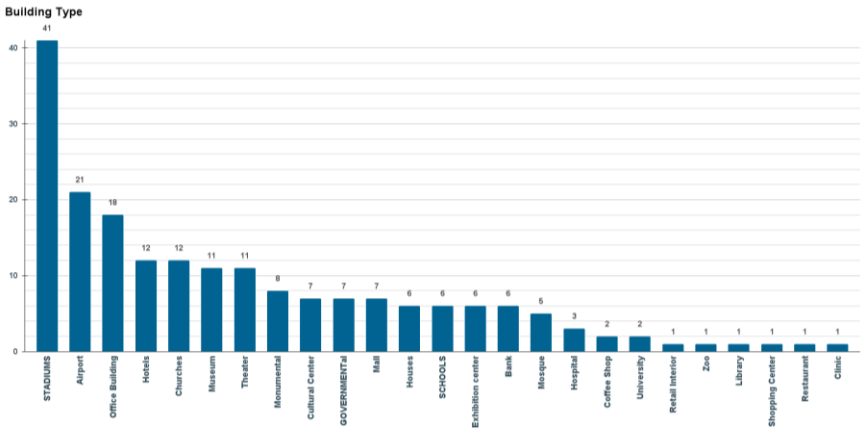


Figure 6. Number of projects in each country in Africa in terms of project types.

In terms of building height as shown in Figure 7, 46.9% of the projects are built as mid-rise buildings, while 35.7% of the projects are built as Low-rise buildings, followed by 15.3% of the projects are built as high-rise buildings, and finally 2% of the projects are built as skyscrapers, noting that the classification is done by considering that the building height is less than or equal 4 floors is considered low-rise, the range from 5 floors to 12 floors is considered mid-rise, while the building height is more than or equal 13 floors is considered high-rise , and finally if the height of the building is over 40 floors then it is considered a skyscraper.

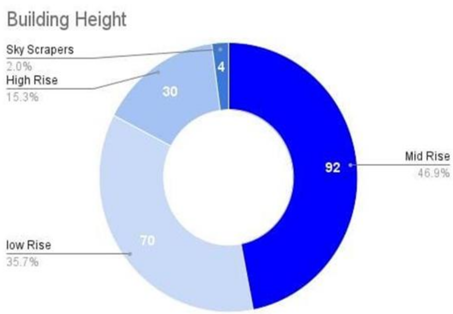


Figure 7. Number of projects in Africa in terms of building height.

It has been noticed, as shown in Figure 8, that 35.53% of the projects were designed by international firms, and 29.44% of the projects were designed by local firms, while 4.57% of the projects were designed by regional firms. Finally, designers for 30.46% of the projects were undisclosed due to the lack of data availability for these projects.

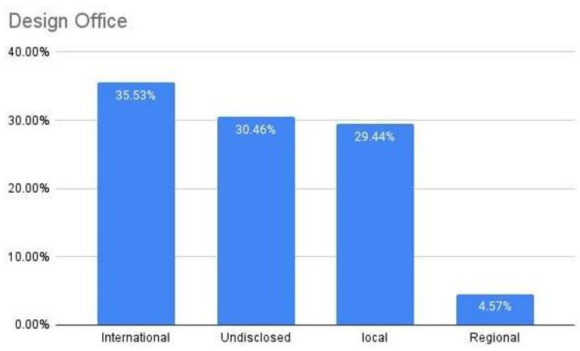


Figure 8. Percentage of projects in terms of the location of design firms.

The highest proportion of projects are found in South Africa and Egypt, where the summation of the projects located in both countries' accounts for a quarter of all projects located on the continent as both countries are with 12.9% and the rest of countries are with 74.1% as shown in Figure 9.

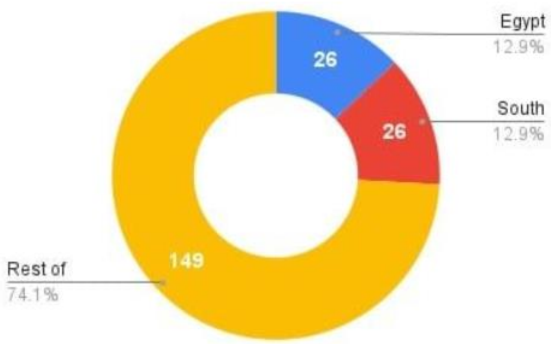


Figure 9. Number of projects in South Africa and Egypt relative to other countries in the continent.

Projects that fall under the interior design and cultural architecture category are the most executed in Egypt, while buildings that belongs to the health care architecture are the least executed there as shown in Figure 10 (Left). On the other hand, buildings that fall under cultural architecture, sports architecture and commercial architecture are the most executed in South Africa while buildings that belongs to the public architecture and educational architecture are the least executed there as shown in Figure 10 (Right).

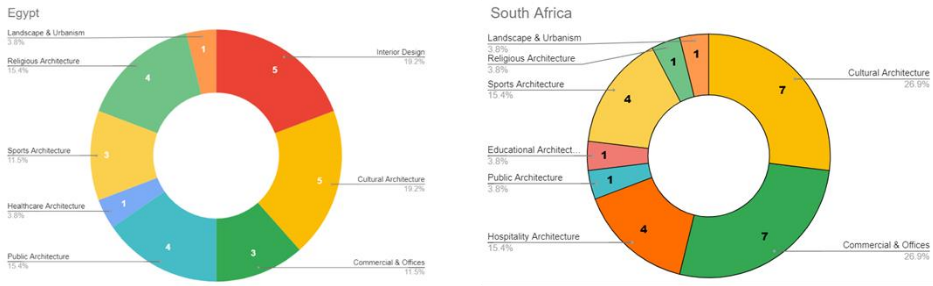


Figure 10. Left: Percentage and number of projects in Egypt in terms of buildings scale, Right: Percentage and number of projects in South Africa in terms of buildings scale.

As for building types, Exhibition centers, airports, and stadiums are the most executed buildings in Egypt, while hospitals, restaurants, and Malls are the least executed there as shown in Figure 11 (Left). On the other hand, malls, museums, and cultural centers are the most executed in South Africa while schools, churches, and airports are the least executed as shown in Figure 11 (Right).

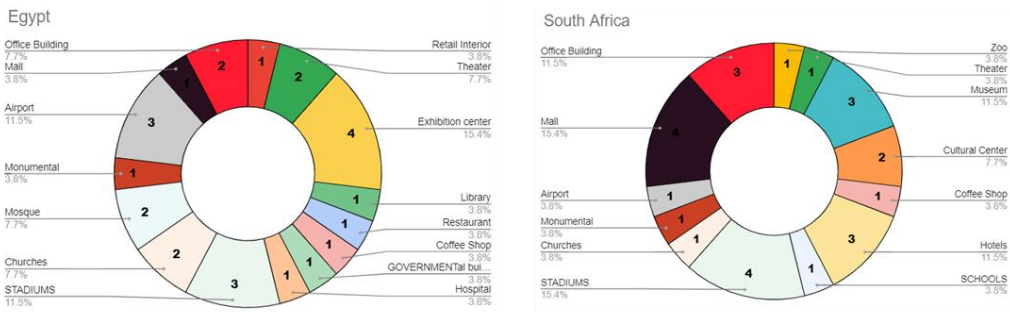
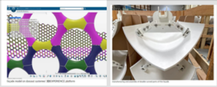
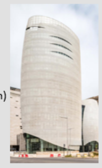


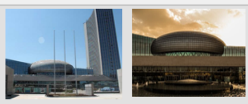
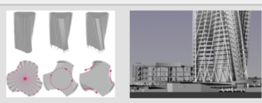
Figure 11. Left: Percentage of projects and number in Egypt in terms of building type, Right: Percentage of projects and number in South Africa in terms of building type.

It is important that the paper represents some of the projects that are characterized by developable and non-developable surfaces in Africa as case studies to support the aim of this research, so in the light of the preliminary research, the case studies were chosen based on data availability, reliability, and representativeness for each region in Africa. Given the aforementioned criteria, the following 10 case studies were selected.

The case studies were analyzed based on the following criteria cost of construction, height of the building, its type, the scale of the building, surface type, the company responsible for the construction, the design firm, its location, the construction materials used, the co-operation of the companies with the researchers in term of exchanging data, digital fabrication techniques, and digital workflow as shown in Table 1.

TABLE 1. Criteria for analysing the projects

Case studies	Orange cote d'ivoire headquarters	Bosjes Chapel	CIMR Tower
			 
	Location: Cote d'Ivoire (southern region) Completion date: 2022 Cost: 72 Million $ Height: Mid rise building Building type: Office building Scale: Commercial and offices Surface type: Developable	Location: South Africa (southern region) Completion date: 2016 Cost: confidential data Height: Low rise building Building type: Churches Scale: Religious Architecture Digital construction method: Non-Developable	Location: Morrocco (southern region) Completion date: 2023 Cost: 14.4 million $ Height: High rise building Building type: Exhibition center Scale: cultural architecture Surface type: : Developable
Construction company:	JET CONTRACTORS	Longworth & Faul	undisclosed
Designer:	koffi and diabaté architectes	Steyn Studio	DL2A
Location:	Cote d'Ivoire	United kingdom	France
IN/Out Africa	In	Out	Out
Continent:	Africa	Europe	Europe
Materials :	glass envelope and plastic skin	Slim concrete cast shell	Concrete, double glass, Aluminum profiles and perforated aluminum for skin
Team support:	Available via email	Available via email	Available via email
Digital fabrication technique	Using Five axis CNC machine and specific mold	-Set-out points and levels plumbed and checked and Trusses placed in position from below and from the top. -38mm timber battens was fixed horizontally as temporary and falsework and Shutter ply was fixed in layers, 12mm + 4mm.	Not found
Digital workflow	3DEXPERIENCE platform and CATIA X-generative design	A total of 584 trusses were designed using Autodesk Inventor	Using Rhino and Revit software

Case studies	AU Conference Center and Office Complex	Pyramids Tower	Twisting tower
			
	Location: Ethiopia (Eastern region) Completion date: 2011 Cost: 200 Million $ Height: High rise building Building type: Governmental building Scale: Public Architecture Surface type: Non-Developable	Location: Egypt (Northern region) Completion date: under construction Cost: not determined yet due to being under construction Height: High rise building Building type: office building Scale: commercial and offices Surface type: Non-Developable	Location: South Africa (southern region) Completion date: 2018 Cost: 53 million $ Height: High rise building Building type: Office building Scale: Commercial and offices Surface type: : Developable
Construction company:	China State Construction Engineering Corporation	Mohamed Talaat Architects	WBHO
Designer:	China Architecture and Design Research Group	Mohamed Talaat Architects (MTA)	LYT Architecture
Location:	China	Egypt	South Africa
IN/Out Africa	Out	In	In
Continent:	Asia	Africa	Africa
Materials :	steel frame	Glass solar panels	Concrete and curtain walls
Team support:	Not Available	Not available	Not available
Digital fabrication technique	Not found	CNC fabrication and 3D printing for model making,	Not found
Digital workflow	Not found	using interoperability workflows connecting Rhinoceros with a BIM platform and other platforms such as SAP	Using Rhino, a 3D CAD program, together with Grasshopper and a graphical algorithm editor.

Case studies

Grand Theatre de Rabat

Location: Morocco (western region)
Completion date: 2017
Cost: 130 million $
Height: Mid rise building
Building type: theater
Scale: cultural architecture
Digital construction method: Non-Developable

Construction company:	Incide Engineering - SGTM Jet Contractors		
Designer: Zaha Hadid Architects	Location:	London	
	IN/Out Africa	Out	
	Continent:	Europe	
Materials :	GRC		
Team support:	Available via email		
Digital fabrication technique	a 3D survey was carried out with a laser-scanner and the information to the site surveyors was obtained directly from the correctly geo-referenced Revit models.	Digital workflow	BIM technology using Revit-Rhino-Grasshopper software

Tree House

Location: South Africa (southern region)
Completion date: 2016
Cost: Not found
Height: Low rise building
Building type: Hotels
Scale: Hospitality Architecture
Digital construction method: Developable

Construction company:	Theunis Naude		
Designer: Malan Vorster Architecture	Location:	South Africa	
	IN/Out Africa	In	
	Continent:	Africa	
Materials :	Corten steel plate, timber and brass for the connection between steel and timber		
Team support:	Not Available		
Digital fabrication technique	The columns, arms and rings are constructed from laser-cut and folded Corten steel plate, and each column is divided into four 'trunks' in the interest of transparency, slenderness and to allow floor beams and windows to pass through the center points of the rings.	Digital workflow	Not Found

Case studies

arch for arch

Location: South Africa (southern region))
Completion date: 2017
Cost: Not found
Height: Low rise building
Building type: Monumental
Scale: landscape and urbanism
Surface type: Developable

Construction company:	Swiss line design		
Designer: snøhetta and local studio / Design Indaba	Location:	Norway	
	IN/Out Africa	Out	
	Continent:	Europe	
Materials :	Larch wood		
Team support:	Not Available		
Digital fabrication technique	The steel arch is made up of 14 sections, each of which was fabricated off-site using a combination of laser cutting and CNC machining. The sections were then transported to the site and assembled using bolts and welding.	Digital workflow	The process involved the use of computer-aided design (CAD) software to create a detailed 3D model of the monument.

Stade de Port-Gentil

Location: Gabon (middle region)
Completion date: 2017
Cost: 71 Million $
Height: Low rise building
Building type: Stadium
Scale: Sports architecture
Surface type: Developable

Construction company:	China State Construction Engineering		
Designer: China State Construction Engineering	Location:	China	
	IN/Out Africa	Out	
	Continent:	Asia	
Materials :	Green steel and golden sheets		
Team support: Not Available			
Digital fabrication technique	Not Found	Digital workflow	Not Found

The digital fabrication method used in most of the case studies is CNC fabrication method and 3D printing for model fabrication. On the contrary, some case studies are built using traditional methods. As for the digital workflow, most of the construction and designing firms use digital software such as 3D cad, Rhino, Grasshopper, and Sap. In terms of exchanging data between the researchers, the designers and the construction firms for sake of this paper, it was found that some firms don't share the data due to confidential agreements with the clients or sometimes these firms don't respond to the emails requesting information about the projects. (See Appendix 1.)

6. Reflection

Looking back at the research conducted there are two categories of information deduced from the collected data. The first category of the two is concerned with the nature of the projects and the practices in Africa. For instance, the division of developable and non-developable exists yet most of the prefabricated surfaces are planner not curved at all. A second observation in regards to the practice in such projects is how the digital technology is utilized only in the design in most of these projects. Yet in the construction phase a more traditional method is preferred. Another important observation, a quarter of these projects is in well divided between Egypt and South Africa the two most affluent countries in the continent. Additionally, the projects presented are due to one of two facilitators. The first one is the Chinese investments in the continent of Africa. This is visible in the collected data through the Chinese consultants being involved in a considerable percentage of these projects. The other facilitator for such projects is them being part of national project pushed by the government of the country on which the project is made such as the new administrative capital of Cairo or the stadiums projects in south Africa for the World Cup.

The second category of observations is concerned with the lack of data on these projects. Firstly, some of the projects are infrastructure ones such as airports. Such typology of projects is one of the reasons there is a lack of data on such projects. Another contributor to the lack of the data is the projects being a product of a Public Private Partnership (PPP) through a special purpose vehicle (SPV). This means to make the projects the government makes with the private sector a company only to construct the project then dissolve afterwards. In addition to that, these companies because of their special purpose nature they do not care for publicity making the information available even more scarce.

7. Conclusion

In conclusion, the analysis and study show that most of these projects are pushed through government, external investors and important events such as World Cup and African Cup of Nations. That's mean the awareness about these technologies should be more widespread in the local market and between the stakeholders. Moreover, the digital technologies in Africa is more utilized through the design process and model simulations. However, the construction process is still done through traditional methods that is because of the lack of knowledge and shortage in resources. An area of research and comparison between digital construction projects in Africa and the global south should be done to provide an international perspective and to evaluate the similarities, differences, and best practices that should take place in Africa. Also, it is highly recommended to make some huge workshops to spread these thoughts and to collaborate the local workers in these workshops and also through some projects. Furthermore, it is suggested to establish an African entity to manage and guide these movements to make them organized and well distributed through all African countries.

8. Appendix

This link refers to the table in which the data is collected by the research team.

https://docs.google.com/spreadsheets/d/17MfIw-U4f9Pxpm4a4YukjRX-rS5vrOwKzzVqnuWg48E/edit?usp=sharing

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EXPLORING THE AFFORDANCES OF DIGITALLY ENHANCED INTERIORS: THE CHILDREN'S SCIENCE CENTER IN MUSEUM GAZHANE

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Abstract. This research delves into the affordances offered by digitally enhanced interior spaces, focusing on the Children's Science Center (CSC) situated within Museum Gazhane in Istanbul, Türkiye. The primary objective is to investigate the impact of physical interiors, which are augmented, modified, or improved through integrating digital technologies and data on children's actions, particularly in rule-based games designed to achieve educational outcomes. The methodology involves on-site observations at the CSC and a comprehensive literature review to gain insights into children's experiences and their awareness of the museum concept. The findings indicate that digital tools and interfaces significantly influence and reshape children's activities within the museum environment. Notably, children prefer realistic and interactive handheld tools that empower them to manipulate and interact with their surroundings at the CSC. Ultimately, this research aims to contribute to the existing literature by providing valuable insights for designing digitally enhanced interior spaces and gamified educational environments tailored to cater to the specific needs of children, leveraging the notion of affordance as a critical keyword in the investigation.

Keywords: *Digitally Enhanced Interiors, Affordance, Children Actions, Rule-Based Play.*

ملخص. يتعمق هذا البحث في الإمكانيات التي توفرها المساحات الداخلية المعززة رقميًا، مع التركيز على مركز علوم الأطفال (CSC) الواقع داخل متحف غازهان في إسطنبول، تركيا. الهدف الأساسي هو دراسة تأثير التصميمات الداخلية المادية، والتي يتم تعزيزها أو تعديلها أو تحسينها من خلال دمج التقنيات الرقمية والبيانات حول تصرفات الأطفال، لا سيما في الألعاب القائمة على القواعد والمصممة لتحقيق النتائج التعليمية. تتضمن المنهجية ملاحظات في الموقع في CSC ومراجعة شاملة للأدبيات للحصول على نظرة ثاقبة لتجارب الأطفال ووعيهم بمفهوم المتحف. تشير النتائج إلى أن الأدوات والواجهات الرقمية تؤثر بشكل كبير على أنشطة الأطفال وتعيد تشكيلها داخل بيئة المتحف. والجدير بالذكر أن الأطفال يفضلون الأدوات المحمولة الواقعية والتفاعلية التي تمكنهم من التعامل مع البيئة المحيطة بهم والتفاعل معها في مركز CSC. في نهاية المطاف، يهدف هذا البحث إلى المساهمة في الأدبيات الموجودة من خلال تقديم رؤى قيمة لتصميم المساحات الداخلية المعززة رقميًا والبيئات التعليمية المصممة خصيصًا لتلبية الاحتياجات المحددة للأطفال، والاستفادة من فكرة القدرة على الكلفة ككلمة رئيسية حاسمة في التحقيق.

الكلمات المفتاحية: *التصميمات الداخلية المحسنة رقميا، الكلفة، تصرفات الأطفال، اللعب القائم على القواعد.*

1. Introduction

Museums are crucial in educating and engaging visitors of all ages, especially children. In recent years, the rapid advancement of digital technologies has revolutionized various aspects of human life, including the design and functionality of these interior spaces. Çetin and Erbay (2021) assert that museums are no longer static; as dynamic spaces, they adopt new practices, especially in terms of visitor-centered approaches. They also argue that museums can communicate effectively with their visitors and offer them a comfortable ambiance where they can interact with their environment, allow them both to have fun and learn, and provide a meaningful museum experience. In this digitally connected era, where children are immersed in technology, it becomes essential to use digital interfaces to capture their attention and provide educational experiences that are engaging, interacting, challenging, and relevant to the child's interests.

The concept of “affordance” plays a crucial role in understanding how these digitally enhanced environments influence human behavior and interactions. Affordance, as defined by Gibson (1979), refers to the perceived and potential actions an individual can undertake concerning their surroundings. In the context of interior spaces, it encompasses the opportunities and constraints presented by digital tools and interfaces, shaping users’ behaviors and experiences. Gamification also becomes important since gamification is one of the approaches that will help increase the interaction among visitors and collections (Ciolfi & McLoughlin, 2012).

The Children’s Science Center (CSC) within Museum Gazhane, located in the vibrant city of Istanbul, Türkiye, represents an exemplary venue to investigate the multifaceted affordances embedded in digitally enhanced interiors. This center provides an interactive and immersive environment where children engage in educational activities through rule-based games facilitated by digitally driven presentations and visualizations. By understanding how these digitally enriched spaces influence children's actions and learning experiences, we can gain valuable insights into designing effective and engaging environments that cater to the needs and preferences of young visitors. This study aims to explore the diverse affordances of digitally enhanced interior spaces by closely observing the CSC within Museum Gazhane. Through a combination of on-site observations and a comprehensive literature study, we seek to shed light on the impact of digital tools and interfaces on children's activities within the museum setting. By examining children's experiences and their awareness of the museum concept, we can better comprehend how these digital affordances contribute to their engagement, learning outcomes, and overall satisfaction.

Informed by the works of Gibson (1979) and other scholars in the field of environmental psychology, this research also endeavors to contribute to the existing literature on designing digitally enriched interior spaces and gamified educational environments. The findings of this study will not only advance our understanding of the role of affordance in shaping user experiences but also offer valuable insights for designers, educators, and museum professionals seeking to create interactive and captivating spaces tailored to children's specific needs. The authors first discuss the physical, cognitive, and spatial qualities of digitally enhanced museum interiors for children in general and then the manifestation of these qualities in CSC through observations and activity-based analysis.

We draw upon relevant literature and research in the field to explore the diverse affordances of digitally enhanced interior spaces at the CSC. Dede (2009) highlights the role of immersive interfaces in enhancing engagement and learning, which aligns with our investigation into the impact of digital tools on children's activities. Furthermore, Frohlich et al. (2014) emphasize the importance of museum exhibits that foster social interactions among visitors, which resonates with our focus on the CSC's interactive environment. Hsieh et al. (2015) discuss the affordances of augmented reality in science education, shedding light on the potential benefits of incorporating such technologies in the museum setting. Jung et al. (2015) provide a comprehensive review of augmented reality, virtual reality, and games for education, supporting the relevance of our study in the context of gamified educational environments.

As we delve into affordance, Kaptelinin and Nardi (2012) offer insights from a mediated action perspective, emphasizing how individuals interact with digital interfaces. Additionally, Kirsh (1995) explores the intelligent use of space, providing a theoretical foundation for understanding spatial affordances within digitally enhanced environments. Finally, Tsekleves et al. (2017) discuss gamifying the design of interactive museum exhibits, and

Vavoula and Sharples (2009) propose a three-level evaluation framework for mobile learning, which is relevant to our exploration of designing engaging and educational spaces for children within the museum context.

Informed by these works, our research aims to contribute to the existing literature on designing digitally enriched interior spaces and gamified educational environments. The findings of this study will not only advance our understanding of the role of affordance in shaping user experiences but also offer valuable insights for designers, educators, and museum professionals seeking to create interactive and captivating spaces tailored to children’s specific needs.

2. Digitally Enhanced Museum Interiors for Children

Integrating digitally enhanced design approaches and interactive technologies in museum interiors presents significant potential for fostering profound learning experiences for children. The case studies presented by Garzotto and Rizzo (2007) highlight the positive impact of integrating technological objects with physical exhibits in well-designed museum spaces. Hall (2005) proposes a set of guidelines to design innovative computing systems that enhance children's learning experiences within museums. The guidelines focus on creating inviting exhibition spaces, incorporating children's contributions, sustaining curiosity, and supporting different visits, ensuring a meaningful and enjoyable experience for young learners (Hall, 2005).

By integrating interactive technologies and digital interfaces into exhibition spaces, museums can transform into child-oriented, gamified environments with diverse interactive experience areas. This transformation creates an inviting, immersive ambiance that ignites children's curiosity and encourages physical activity. Creating game-based learning environments for science museums raises challenges distinct from those raised by games for classrooms. In addition to serving distinct learner demographics and emphasizing different areas of learning, museums, and classrooms provide varying degrees of learner autonomy (Rowe et al., 2017). Addressing these challenges, Rowe et al. (2017) identify several design factors for creating game-based learning exhibits in science museums. These factors include providing a low barrier to entry, fostering exploration and curiosity, delivering immediate and dramatic feedback, prioritizing visually appealing aesthetics with broad appeal, leveraging novel hardware platforms, and providing flexible user experiences. To understand how such design factors adapt in response to children's actions, the initial step involves identifying the affordances of the museum environment. In the following sections, we explore the contributions of gamified museum interiors and the affordances of digitally enriched spaces to children's physical actions.

2.1. GAMIFIED MUSEUM INTERIORS

Playing games is often considered a series of essential activities that are crucial to children's growth and development and in which it is most readily observable how developmental milestones take place. Piaget (1962) asserts that children learn through play in his ideas of cognitive development, which he advanced based on his observational research on children. Play is a vital component of a child's self-development and is directly related to physical and cognitive growth in all the titles. According to Piaget (1962), the conditions that make a game a cognitive activity include excitement, experiencing, organizing information, adding new circumstances and knowledge to the repertory, and maintaining the balance that the game inevitably needs.

Play can be argued to be the most potent motivator that ensures the participation of visitors in gamification applications in digitally enhanced museums. Landers et al. (2018) define gamification science as a social scientific, post-positivist subdiscipline of game science that explores the various design techniques, and related concerns, that can be used to add game elements to existing real-world processes. Gamified content expands children's range of actions and diversifies their encounters. Children are drawn to such integrations as tangible visualizations, haptic interfaces, or hands-on kiosks that engage the senses and physical activities in these integrations in a museum created specifically for educational purposes. About the exhibition of physical samples, the use of digital resources proves to be beneficial because it enables visitors to have a better understanding of objects and ideas since it allows offering complementary information in a more attractive way for visitors without overloading the exhibitions environment with an excess of information (Vaz et al. l, 2018).

Game-based learning approaches support informal museum settings that educate children through technology-driven museum experiences. Din (2016) asserts that the benefits of creating such games are to provide digital engagement, expand vocabulary, customize learning experiences, extend thinking processes, develop strategic planning and problem-solving skills, and promote generalization to broader ideas and applications. In the context of modern learning approaches, Beavis (2014) claims that digital games are used successfully to draw in kids and teenagers and boost their motivation for learning.

Presenting gamified content for children in a museum environment with digital tools can contribute to extending their action repertoire and diversifying their actions with their experiences. Kay and Ozkar (2020) present a study exploring digital augmentation as an integral part of children's spatial experience with physical objects. They introduce a blended play environment that combines digital and physical media to enhance children's physical activity and play through tangible interactions, offering different interaction paths. Gamification is the process of changing an already existing activity using game elements so that people can be attracted and motivated (Landers et al., 2018). Particularly during museum visits, gamified exhibition content helps children experience excitement and adventure with free actions. In digitally enhanced museums, the primary motivation is to capture children's attention using educational content delivered through digital tools, such as touch screens or hands-on objects.

2.2. AFFORDANCES OF DIGITALLY ENHANCED MUSEUMS

Affordance, originally conceived by Gibson (1979) in ecological perceptual psychology, pertains to perceived physical opportunities within a given environment during action. Norman (1999) refines this as the relationship between an object's properties and an agent's capabilities, dictating its possible uses. Kytta (2004) argues that individuals perceive environmental potential for action when their physical attributes, abilities, social needs, and intentions align with the environment's features. Kim et al. (2007) emphasize human-based affordances, where individuals create opportunities using their bodies or belongings, prompting reevaluation by interior architects. This concept guides environmental design, focusing on the interaction between individuals and their surroundings. The affordance-matching hypothesis (Bach et al., 2014) suggests that object knowledge aids in predicting and understanding others' actions, acting as a bridge between goals and motor systems.

This study investigates digitally enhanced museum affordances, with a focus on users' physical interactions with objects. Creating digitally enriched gamified museum interiors involves incorporating technologies like sensors, touchscreens, haptic interfaces, interactive projections, augmented reality, and virtual reality. Vaz et al. (2018) explore emerging technologies such as 3D printing, virtual reality, location-based beacons, wearable tech, and tangible user interfaces, which offer interactive exhibits and simulation experiences, enhancing children's understanding of museum concepts. Franco et al. (2015) introduce "new visual technology experiences" to strengthen interaction and user interest in the exhibited products. These experiences encompass haptic interfaces, AR, VR, and 3D rapid prototyping techniques, which enhance children's understanding and engagement with museum exhibits.

3. The Children's Science Center at Museum Gazhane

The Hasanpaşa Gazhanesi, a coal-fired gas factory established in 1892 in Istanbul's Kadıköy district, once powered the Anatolian side of the city until its closure in 1993. In 2021, it was transformed into the Museum Gazhane, a cultural and artistic center, by do[x]architecture. This revamped space, featuring a climate crisis theme, now includes a climate museum, a cartoon museum, a children's science center, exhibition rooms, theaters, libraries, and social areas (Figure 1).

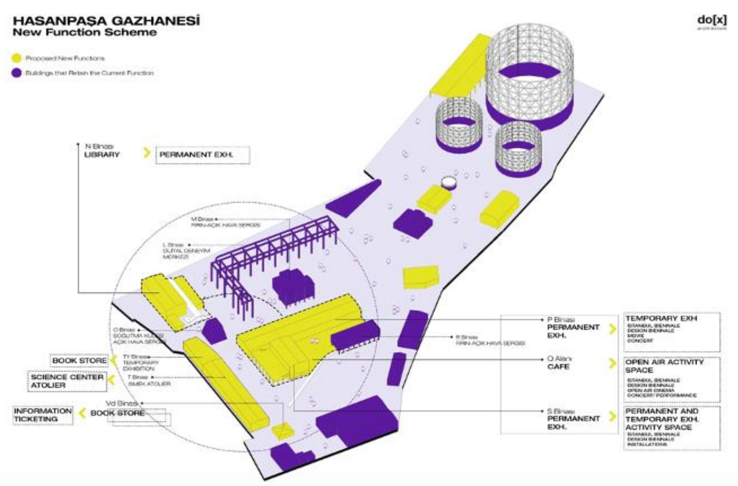

Figure 1. Museum Gazhane, New Function Scheme (Do[x]Arch).

The Museum Gazhane exemplifies adaptive reuse, transforming an industrial site into a dynamic cultural hub. It has quickly become a popular attraction in Istanbul, catering to a diverse audience. This unique learning space for children stands out in the city due to its expansive campus, which includes multiple buildings and outdoor areas. In contrast to the closed narrative environment of the CSC (Children's Science Center), Museum Gazhane offers a more open, flexible, and hands-on learning experience through its interactive exhibits (Figure 2).

Figure 2. Children’s Science Center, Museum Gazhane, Istanbul, Türkiye (Keskin, 2023).

3.1. DESIGN AND FEATURES OF THE CHILDREN'S SCIENCE CENTER

Science Centers supported by the Scientific and Technological Research Council of Turkey (TUBITAK) aim to spread science culture and increase interest in science in Turkey. The CSC features interactive exhibits on energy designed with guidance from leading science centers. The designers of the project described the CSC as follows: "Gazhane's building (T Building), which was used as a workshop and warehouse in the past, functioned as a science center with experience units on the axis of the energy and climate crisis, and a workshop area for children… Concerns about holistic planning are top of mind in the experience area. The units were arranged according to their significant headings and put in the circulation system to maintain the sense of space without using any separator walls. The tables, which include the technological infrastructure and apparatus of the units, were created using people with special needs and the wheelchair approach in mind. Dark colors were preferred for the floor, walls, and furnishings in the experience area to highlight the experience units and games" (Do[x]Arch.).

The CSC comprises a collection of rule-based games strategically positioned within the axial layout of kiosks. These games encompass a range of digital content, delving into topics including comprehension and conversion of energy, diverse energy classifications, energy application, consumption, and its prospective ecological implications. Each of the 21 distinct game kiosks is categorized into three primary sections, namely, "Energy Understanding," "Energy Forms," and "Energy Utilization." The explanations including game rules give some clues about visitors' actions in the digitally enriched interior (Figure 3).

	Kiosk Tittles	Game Rules for the Digitally Enhanced Kiosks		Kiosk Tittles	Game Rules for the Digitally Enhanced Kiosks
1	you are energy	Watch the exhibition video on ocean tides. Ponder the reasons for tidal occurrences. Examine global warming from 1880 to 2020.	11	lighting energy	Press the button on the left and observe the lightning between the spheres. Press the button on the right and observe the move of the lightning between the wires.
2	motion energy	Press the pump to push water to the system. When you have enough water in the system, press one of the buttons to release water.	12	uranium	Slide the lever to right and left. Read the name of the element on the screen. Follow the information about the element on the screen.
3	gravitational energy	The button is pressed to start the kiosk that is not actively used. The movement of the object placed to observe gravity is examined.	13	seismic energy	Construct a building with the pieces in the box. Start the earthquake simulation by pressing the button on the exhibit. Turn the potentiometer on the right in order to adjust the magnitude.
4	simple machines pulleys	Try to lift the weight by pulling the rope connected to moveable pulley. Try a block and tackle pulley to lift the weight.	14	geothermal energy	Examine the transformation of resources by spinning wheels in the exhibition. More energy will be released when multiple users experience the kiosk at the same time.
5	generator and complete circuits	Pull the generator lever and observe the lights and observe the lights' response. Push the magnet on the generator lever into the generator. Rotate the lever with the magnet and observe the lights' response.	15	wind energy	Start the fan by pressing the button on the exhibit. Direct the wind towards the wind turbines by adjusting it by its handles. Position the fan for optimum turbine impact. Observe city lights turning on.
6	transform energy	Choose language preference with the exhibit button. Start the experiment by pressing "start." Observe the energy type and transformation.	16	tidal energy	Lift up and down the kiosk's arms to create waves with the water inside. Observe how tidal power uses the water to generate electricity.
7	thermal power station	Press the button to start the mine cart. Observe the burning process and steam turbine in action. Witness the electrical energy transmitted to the city.	17	efficient use of energy	Select language preference. Press "start" to begin the experiment. Calculate the shortest delivery route. Place the colored packages representing the cargoes in the trailer of the truck in order of delivery.
8	nuclear power station	Press the button to start the nuclear reaction. Rotate the potentiometer on the kiosk and move the rods in the nuclear power plant adjusting the nuclear reaction speed. Observe thermal energy boiling water in the power plant.	18	greenhouse gas	Choose language preference with the exhibit button. Start the experiment by pressing "start." Answer questions about energy generation and consumption. Select the option with the least greenhouse gas emissions.
9	solar energy	Start the projectors by pressing the button on the kiosk in the middle of the exhibit. Move the mirrors by holding its handles to reflect projector's light to the solar panels on the planes above.	19	energy from waste	Select your language preference by using the button on the exhibit. Initiate the experiment by pressing the start button. Activate the necessary section of the facility with the buttons.
10	oil and natural gas	Examine the transformation of resources by spinning wheel in the exhibition. Discover the reflections of the use of resources in daily life by watching the screens in the exhibition and the movement of the kiosk.	20	green energy	Choose language preference with the exhibit button. Press "start" to begin the experiment. Observe the suitable green energy facility for different environmental conditions.
			21	interactive wall	Touch one of the energy boxes on the wall and transmit energy to a part of the city. Watch the animation in the area that you transmitted energy.

Figure 3. Game Rules of Kiosks at CSC. (Keskin, 2023).

3.1.1. Affordances Provided by Digitally Enhanced Kiosks in the Children's Science Center

The digitally enriched kiosks within the CSC have the potential to disclose a multitude of affordances through their interactive functions. The inherent possibilities for interaction and engagement within this environment are virtually limitless. However, it is essential to recognize that the action possibilities provided by these kiosks can be systematically classified based on their functional properties. A series of studies (Heft, 1988; Kytta, 2003, 2004; McLaren et al., 2012; Atmodiwirjo, 2014) involving children's interactions with distinct spatial configurations and objects found within the activity setting have resulted in the categorization of activities based on their functional attributes. Atmodiwirjo (2014) suggests the need for a design that focuses on how the physical features of objects and spaces might be used in different ways for body actions and how they might trigger adaptive actions. McLaren et al.'s (2012) study identified a comprehensive set of classroom affordances used by all children. Their conceptual framework emphasizes individual capacity, or "what each child's body could do" to overcome environmental constraints and discover new ways of moving (McLaren et al., 2012).

Objects and spaces offer specific actions based on their dimensions, aligning with the user's body and body parts involved in the interaction, as proposed by Heft (1988). Within the CSC context, kiosks provide a range of physical action possibilities, enabling diverse learning experiences for children. Given children's limited physical abilities and the unique spatial characteristics of CSC's kiosks, various physical action options and sequences are evident (see Figure 4). Figure 4, adapted from Heft's (1988) functional taxonomy of children's outdoor environments, illustrates various spatial properties inherent in digitally enhanced kiosks and their potential for physical actions.

Visitors to the CSC can observe and listen to kiosks to understand their different features and sounds. They can press buttons, grip handles, or explore textures and surfaces through touch. Furthermore, children can attempt to reach varying heights on the kiosks or manipulate objects within them. The diverse ways in which children utilize these spatial features result in distinct action sequences. While some kiosks offer limited actions, others provide numerous possibilities, highlighting the adaptability and variability of the kiosk environment in accommodating various interactions.

Kytta (2003) discusses the concept of affordances in different environments and their relation to individuals. All environments contain numerous potential affordances that have yet to be perceived by anyone. The realization of a potential affordance demonstrates how these opportunities exist between the individual and the environment. Perceived, utilized, and shaped affordances represent various levels of actualized affordances. Each person perceives, uses, and shapes affordances that align with their personal qualities (Kytta, 2003). This study categorizes potential actions in the CSC based on the physical capabilities of preschool-aged children and their motor skills.

The categorizations are presented in Figure 4, entitled perceived affordances, utilized affordances, and finally shaped affordances as delineated within Kytta's (2003) framework denoted as "Levels of Affordances." Perceived affordances require little effort or acceptable motor activity, such as watching, listening, touching, or pressing. Utilized affordances require more effort and involve larger muscle groups, such as reaching higher. Shaped ones are the most complex and require fine and gross motor skills, such as constructing blocks or pulling and pushing objects. Perceived affordances initiate interactions with the digitally enhanced kiosk, triggering subsequent utilized and shaped affordances driven by rule-based games. For instance, the "tidal energy" kiosk starts with observation and progresses to physical engagement as children reach for the given object and finally pull or push the object. These evolving actions form sequences, each triggering the next, creating engaging challenges. Through this, active motor skill utilization enhances contextual learning and the child's enjoyment.

	Spatial Properties	Levels of Affordances			Example of Spontaneous Action Sequence
		perceived	utilized	shaped	
1	Horizontal-vertical, flat-hard surfaces elevated from the floor level to child's height, screens on floor level	Watching (screen), Touching	Stretch (out)		
2	Curved, hard surfaces elevated from the floor level to child's height, screens on high level, collaborative play	Watching (screen), Touching, Pressing (buttons)		Pushing, Pulling	
3	Curved, hard, levels arranged one on the top of the another horizontally or diagonally	Watching (screen), Touching	Stretch (out)		
4	Flat-hard surfaces elevated from the floor level above slightly child's height	Watching (screen), Touching	Stretch (out)	Lifting, Pulling	
5	Flat-hard surfaces elevated from the floor level above slightly child's height	Watching (screen), Touching	Stretch (out)	Pulling, Pushing, Rotating (object)	
6	Flat-hard surfaces elevated from the floor level to child's height	Watching (screen), Touching, Pressing (buttons)			
7	Horizontal-vertical, flat-hard surfaces elevated from the floor level above child's height	Watching (screen), Listening, Touching, Pressing (buttons)			
8	Horizontal-vertical, flat-hard surfaces elevated from the floor level above child's height	Watching (screen), Listening, Touching, Pressing (buttons)			
9	Curved, hard surfaces elevated from the floor level to child's height, screens on high level, collaborative play	Watching (screen), Touching, Pressing (buttons)	Holding	Moving (object)	
10	Horizontal-vertical, curved, hard, levels arranged one on the top of the another horizontally or diagonally, collaborative play	Watching (screen), Listening, Touching, Pressing (buttons)	Stretch (out),	Moving (object), Rotating (wheel)	
11	Flat-hard surfaces elevated from the floor level to child's height	Watching (screen), Touching	Stretch (out),		
12	Flat-hard surfaces elevated from the floor level to child's height	Watching (screen), Touching, Pressing (buttons)	Stretch (out),	Sliding (object)	
13	Flat-hard surfaces elevated from the floor level above slightly child's height, objects, collaborative play	Watching (screen), Listening, Touching, Pressing (buttons)	Stretch (out), Holding,	Constructing (blocks)	
14	Vertical, curved, hard surfaces elevated from the floor level above slightly child's height, collaborative play	Watching (screen), Listening, Touching	Stretch (out), Holding	Rotating (wheel)	
15	Flat-hard surfaces elevated from the floor level above slightly child's height	Watching (screen), Touching, Pressing (buttons)	Stretch (out),	Sliding (object)	
16	Vertical, hard surfaces elevated from the floor level above slightly child's height, sound produced by the movement of water, collaborative play	Watching (screen), Listening, Touching	Stretch (out), Holding	Lifting, Pulling, Pushing, Moving (object)	
17	Flat-hard surfaces elevated from the floor level to child's height, objects	Watching (screen), Touching, Pressing (buttons)	Holding	Moving (object), Placing (blocks)	
18	Flat-hard surfaces elevated from the floor level to child's height	Watching (screen), Touching, Pressing (buttons)			
19	Flat-hard surfaces elevated from the floor level to child's height	Watching (screen), Touching, Pressing (buttons)			
20	Flat-hard surfaces elevated from the floor level to child's height	Watching (screen), Touching, Pressing (buttons)			
21	Flat-hard surfaces elevated from the floor level above child's height	Watching (screen), Touching			

Figure 4. Levels of Affordances within Digitally Enhanced Kiosks at CSC. (Keskin, 2023).

Museums often aspire to provide an array of physical interactions and hands-on experiences to actively engage children and render their visits enjoyable and memorable. At the CSC, there is a deliberate encouragement for children to partake in tactile exploration and interaction with objects located in purposefully designed hands-on areas and exhibits. This engagement frequently involves pressing buttons to elicit sounds, lights, or movements; manipulating controls to modify settings or instigate actions; and utilizing touchscreens to navigate digital content. Interactive stations at the CSC integrate features such as button pushing and control operation, frequently incorporating interactive displays endowed with buttons, switches, levers, or touchscreens. Children can handle artifacts, manipulate puzzle pieces, operate mechanical displays, or touch tactile materials to garner a tactile understanding of the objects. They may encounter structures to reach, tubes to carry, or play areas that invite gross motor activities, including running, jumping, balancing, or reaching, thus fostering physical exploration, and providing space for active play (see Figure 5).

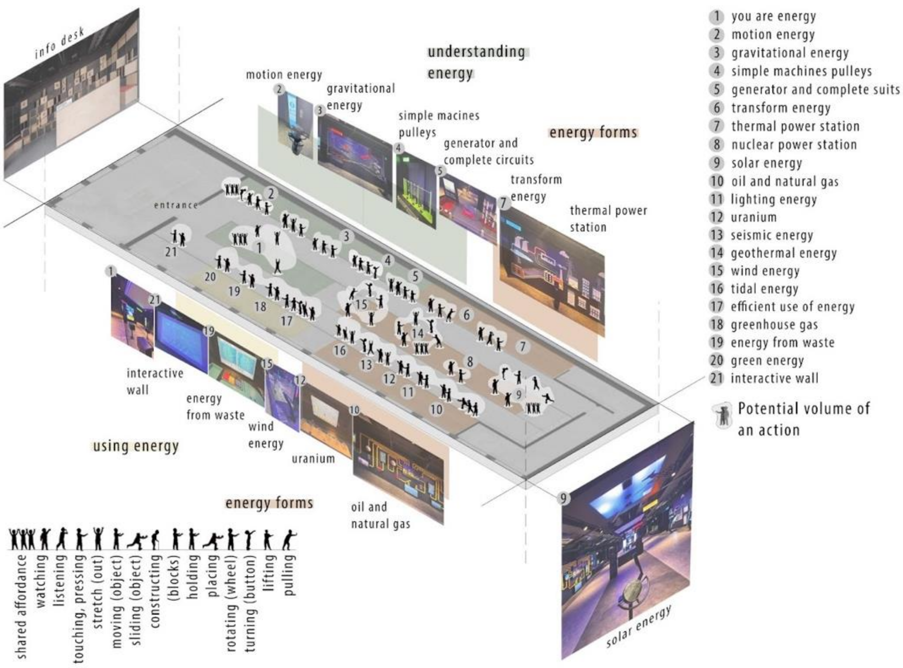

Figure 5. Children’s Action Possibilities and Circulation at CSC. (Çalcalı, 2023).

It is essential to consider that the specific physical actions available to children in CSC can vary depending on the museum's exhibition stations, target age group, and interactive elements. Such diversity in the sense of physical acts offers enjoyment and bridges the gap between the intangible (rules, procedures, logic, etc.) and the tangible (the physical settings) with personal affordances. Rules are no more abstract; they manifest themselves in dependence on physical and mental capabilities. Moreover, the consequences also vary according to children's success. This triggers new trials to improve the first results, increasing engagement time and joy.

3.1.2. Enhancing Museum Experience of Children through Digital Tools

Digitally enhanced kiosks at the Children's Science Center (CSC) offer gamified experiences beyond physical interactions, enabling children to comprehend environmental issues. Children explore and learn complex environmental concepts through games, promoting experiential learning. The digitally enhanced kiosks with dynamic interactions promote engaging and meaningful learning experiences for children within the context of play. Kay and Ozkar (2015) view play as a rule-setting activity that bridges the child's intentions with visual perceptions. In this context, children become active agents interacting with the digital setup, establishing new connections between their bodies and the on-screen images and movements. The CSC's digital content empowers children to set rules, establish visual and spatial connections, and spontaneously interact with the exhibition space during play.

During their museum visits, children may engage in sensory actions while visiting museums, including sound exploration, smell stations, visual stimulation, tactile experiences, kinetic experiences, taste exploration, and multisensory installations. Almost all stations at CSC are multisensory installations, and they have kiosks where children use their sense of touch, visual and auditory. These multisensory installations stimulate multiple senses simultaneously, allowing children to step into immersive environments featuring synchronized visuals, sounds, and tactile elements, providing a holistic sensory experience. Children can also interact by pressing buttons to produce different sounds, experimenting with musical instruments, or using sound-generating devices to create their auditory experiences. Additionally, they may engage by observing optical illusions, viewing visual projections, or interacting with visually stimulating exhibits. It is essential to note that each child's museum experience can be unique, with variations in their actions and levels of engagement.

At the CSC, digital interfaces serve as bridges between abstract concepts and concrete experiences, facilitating hands-on learning and encouraging active engagement. Garzotto and Rizzo (2007) observed that children's movements and interactions in this space are influenced by intentional motivations and contextual affordances, making the design of effective and coherent contextual affordances crucial yet challenging in digitally augmented museum environments. Children can explore the museum through interactive displays, touch screens, and hands-on objects combined with tangible exhibits during their CSC visit. While there is an established order of kiosks within the museum context, each with its own set of game rules, the axial layout of the space grants children the freedom to engage in spontaneous, unrestricted play.

Children can freely explore the museum, move from one kiosk to another, and experiment with various activities at their discretion.

4. Discussion, Implications and Limitations

In recent years, museums have undergone a significant transformation with the advent of digital technologies. Designers have created dynamic and responsive digital interfaces that captivate children's attention. In this study, we have examined the affordances present in digitally enhanced interior spaces, focusing on the Children's Science Center (CSC) located within the Museum Gazhane in Istanbul, Türkiye. The study is limited to exploring a small sample size of preschool-aged children without a control. Parallel to this fact, the study stands on the qualitative side of the question of "how children can act around digitally enriched kiosks," considering their limited physical abilities.

Affordances that enhance children's engagement with the interior have commonly been addressed in the literature from an activity-based perspective, often found in guides promoting physically active play (Guthold et al., 2018; WHO, 2019). However, activities incorporate direct actions as integral elements, so focusing on actions gives a detailed and sequential analysis of the activity. The study focuses on the action possibilities in the relationship between children and digitally enriched kiosks and questions on enhancing children's engagement. This research categorizes actions into three groups: "perceived," "utilized," and "shaped" according to their level of affordances. Notably, when the potential actions within kiosk interfaces span all three of these diverse categories, they contribute to the learning experience more and become more joyful.

This study contributes to the field by offering both a state-of-the-art and a new discussion on the integrity of varying physical engagement opportunities for children in digitally enhanced interiors. Affordances specify the range of possible activities, but affordances are only helpful if they are comprehensible to the users. In designing a digitally enhanced museum environment for children, we must question how to design conditions to facilitate children's different play patterns while supporting bodily affordances. In this respect, the study provides valuable insights into the affordances of digitally enhanced interior spaces at the CSC. The findings underscore the importance of designing accessible and coherent environments with visible affordances to support children's active engagement and explorative attitude.

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LEVERAGING LANDSCAPE ARCHITECTURE AND ENVIRONMENTAL STORYTELLING FOR NEXT-GENERATION GAMING EXPERIENCES

A Holistic Approach to Virtual World Design

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Abstract. Designing a virtual environment within a digital game occupies a large part of the design procedure, requiring holistic attention and a broad arrangement of the game constituents. Considering other design disciplines, they occupy a unified design methodology; however, a comprehensive literature review reveals the lack of the intended design methodology in the digital game domain's virtual environment development, despite a currently proposed theoretical methodology trying to dissolve the issue. Hence, this research aims to determine the industry's requirements and provide a set of assets included in current digital games as an initial step of providing such a design methodology for the domain. In this regard, the researchers reverse-engineered ten selected digital games, understanding the current condition of digital games via adopting the mentioned currently available design methodology. This dataset reveals a lack in the assets of the story layer in the recent digital games, despite their focus on being story-based. This dilemma leads to long text or speech conversations between game characters, disrupting the players while following the game. The current design focuses on environmental resources only, however, as a virtual landscape, the story needs to be reinforced to be a balanced and well-designed game. Hence, increasing the ratio of the assets in this layer will advance the games' interactivity. Also, as future work, this data set could pave the way for a digital game industry design tool regarding the virtual environment.

Keywords: *Digital game, Level design, Landscape Architecture, Virtual Environment.*

ملخص. يشغل تصميم بيئة افتراضية ضمن لعبة رقمية جزءًا كبيرًا من إجراءات التصميم، ويتطلب اهتمامًا شاملاً وترتيبًا واسعًا لمكونات اللعبة. عند النظر في التخصصات التصميمية الأخرى، فهي تحتل منهجية تصميم موحدة؛ ومع ذلك، يكشف استعراض الأدبيات الشامل عن نقص في المنهجية التصميمية المقصودة في تطوير بيئة اللعبة الرقمية الافتراضية، على الرغم من المنهجية النظرية المقترحة حاليًا التي تحاول حل المشكلة. وبالتالي، تهدف هذه الدراسة إلى تحديد متطلبات الصناعة وتقديم مجموعة من الأصول المدرجة في الألعاب الرقمية الحالية كخطوة أولية لتقديم منهجية تصميم مثل هذه للمجال. في هذا الصدد، قام الباحثون بالهندسة العكسية لعشر ألعاب رقمية مختارة، فهموا الحالة الحالية للألعاب الرقمية من خلال اعتماد المنهجية التصميمية المتاحة حاليًا. يكشف مجموع البيانات هذا عن نقص في أصول طبقة القصة في الألعاب الرقمية الحديثة، على الرغم من تركيزها على أن تكون قائمة على القصة. هذا الجدل يؤدي إلى محادثات نصية أو خطابية طويلة بين شخصيات اللعبة، مما يعكر صفو اللاعبين أثناء متابعة اللعبة. يركز التصميم الحالي فقط على الموارد البيئية، ومع ذلك، كمناظر طبيعية افتراضية، يجب تعزيز القصة لتكون لعبة متوازنة ومصممة بشكل جيد. وبالتالي، سيؤدي زيادة نسبة الأصول في هذه الطبقة إلى تقدم تفاعل الألعاب. أيضًا، كعمل مستقبلي، يمكن أن يمهد مجموع البيانات هذا الطريق لأداة تصميم صناعة الألعاب الرقمية فيما يتعلق بالبيئة الافتراضية.

الكلمات المفتاحية: *لعبة رقمية، تصميم المستوى، تنسيق المواقع، البيئة الافتراضية.*

1. Introduction

Among global industries, the digital game industry, with its large market size, is a fast-growing one with an average rate of 11% per year since the 1962s (Hudrasyah et al., 2019), the development year of the first computer game ever (Zackariasson and Wilson, 2010). Currently, its market size is rising above the digital media market (Lange et al., 2021) and surpassing the movie and music industries in revenue (Guðjónsson, 2020). The rise of mobile gaming has significantly contributed to this growth, with mobile games accounting for nearly half of the global games market in recent years (Newzoo, 2019). In more detail, the digital game market generated 196.8 billion USD in revenue for 2022 and is estimated to increase to 268.8 billion USD in 2025 (Newzoo, 2022; Statista, 2023). Specifically, with the COVID crisis emerging, the digital game market trend in 2020 has been influenced. More people prefer indoor activities to avoid infection; accordingly, the game industry is developing more actively (Unity, 2020). E-sports, too, has seen a surge, with its global audience growing to nearly half a billion in 2020 (Statista, 2020). Even after the crisis ended, such a growth trend did not end. Hence, the design process of digital games is getting more critical than ever in the current era. Since the market size is getting more extensive than ever, more people are playing games. Additionally, people are asking for more advanced and sophisticated levels of games. This level is highly dependent on the level of the virtual landscape due to taking the most significant part of the content.

The advancements in game engines, like Unreal Engine and Unity, have enabled developers to create more immersive and realistic game worlds. However, to develop a digital game, the developers should consider various aspects of design, including a detailed virtual environment, as the most time-consuming one, requiring a comprehensive consideration of the game's multiple components through a considerable number of human resources (Kim, 2020). According to Choi (2010), the effort required to design a virtual environment in a digital game equals the amount needed to develop the game. Hence, designing and building it is the same as real space. Furthermore, the characteristics of the digital game are indeed the characteristics implied by its virtual environment (Apperley, 2006). The intricacy of these virtual environments has grown with the advancement of technology, demanding more detailed graphics, realistic physics, and dynamic interactions, further complicating the design process (Anderson, 2012; Eshaghi et al., 2021). However, finding a standardized design methodology for designing and producing any virtual environment is challenging. Therefore, digital game companies follow various methodologies for each project they start, which requires a significant share of work and time (Huijser et al., 2010; Kim et al., 2018; Afshar et al., 2022). This lack of standardization often leads to increased costs and extended development cycles, especially when teams need to familiarize themselves with different methodologies for each new project (Sotamaa, 2010). Hence, with the absence of a unified and standardized design methodology, the virtual environment design process is inefficient, with low quality and unstable results (Kim, 2020; Afshar et al., 2022). Moreover, the rapid evolution of gaming platforms and user expectations further exacerbates these challenges, making it imperative for the industry to consider more streamlined approaches (Juul, 2010).

On the other hand, various domains such as architecture, landscape architecture, and urban planning have been applying multiple design methodologies throughout history, easing the space creation process and leading to better quality results. Unfortunately, such a concept is currently lacking in the digital game industry. With this background, a methodological design approach is needed for the digital game industry, accessible by understanding and applying the current situation and the solution to the lacking parts. Hence, as the first stage to fulfill this lack, the research aims to determine the game industry's requirements to propose a dataset of the available virtual environment assets in various digital games. This dataset could enable the development of a possible future tool to ease the digital game industry's process in the virtual environment part of game development.

2. Literature Review

Studies focusing on the virtual environment are available in the literature; however, figuring out the existing research, notably, all the researchers took advantage of virtual spaces to design a better real space in landscape architecture, architecture, and urban design. Throughout a comprehensive literature review, we can instance the following examples. Landscape architects can visualize a concept or idea, or architects can archive their designs more efficiently via a comprehensive understanding of the virtual space as a tool (Portman et al., 2015). 3D virtual spaces can be used for more accurate duplication and analysis of real space gardens (Li and Dawei, 2017; Wang and ZhenNan, 2010). For a more efficient design of real spaces, an automated methodology and program had been developed for the landscape architects (Deussen, 2003). Also, to design and present the landscape architect's idea more efficiently, two existing studies tried to propose a new methodology using virtual space (Lombardo, 2018; van Lammeren et al., 2002). Moreover, the use of virtual space for efficient landscape architecture education is another focus of the researchers. Johns and Russell (2005) treat the digital game engine, a virtual environment design tool, as an education method for students. In another similar attempt, Francis (2001) focused more on observing and preserving landscape architecture case studies. Additionally, in the literature, Building Information Modeling (BIM) or Landscape Information Modeling (LIM) is used as a tool to simulate real space virtually by combining them with virtual spaces and game engines (Ahmad and Aliyu, 2012; Boeykens, 2011; Döllner and Hagedorn, 2007; Ma and Bing, 2017).

The main focus of the existing studies about the virtual environment is oriented around using it as a tool to pave the way for efficiency or quality in real-space design. Despite this, enhancing the quality of the virtual environment by using real space design techniques has rarely been studied. For instance, visionary architecture that facilitates the architects to pass beyond the real restrictions and visualize their exemplary ideas virtually (Collins, 1968) has highly superficial results that play a critical role in space design. The drawing of Herron as the 'Walking City' (Ron, 2021) or Sant'Elia's vision of the future urban environment (Landes, 2016) are some examples of the issue. However, since the outcomes are visual materials showing the architect's abstract concept, it would be controversial to call them interactive spaces. So, even this sample of using the virtual environment as a design domain is not adequately efficient in enhancing real space.

Regarding the studies considering the virtual environment as a design area, references are still rare (Kim, 2016; Kim et al., 2018; Kim, 2020). This research series adopts the design methodology of landscape architecture, architecture, and urban planning domains to enhance the efficiency and quality of the virtual environments. In more detail, firstly, the researchers compare and analyze the differences between real and virtual spaces as a design domain (Kim, 2016), discovering the classification possibility of virtual landscapes based on their characteristics compared to real spaces. In this research, a classification methodology is first proposed, and then the researcher developed a digital game design methodology (Kim et al., 2018) validated with the comparative experiments (Figure 1).

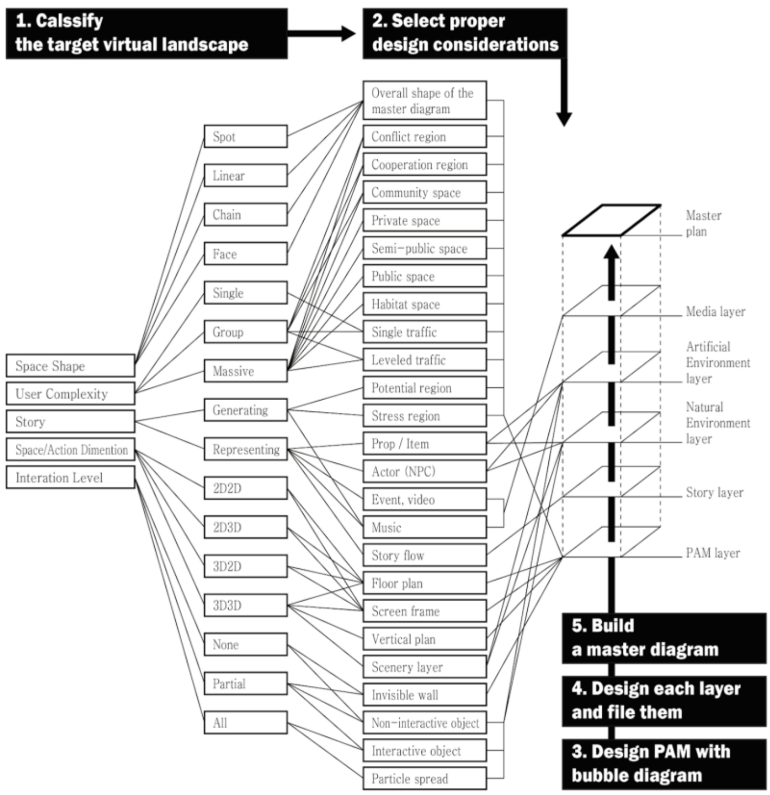

Figure 1. Digital game classification and design methodology.

As the research results indicate, designers who have learned the methodology experienced 15 times higher work efficiency and more than three times higher cooperation with their mates. Additionally, the final results were highly satisfactory in terms of quality (Bazin and Kim, 2018). So, for this reason, we decided to adopt Kim's design methodology as the primary reference of the study.

3. Methodology

Since the research aims to understand the requirements of the game developers, designers, and artists, the first step of the study is to determine the needs of a digital game regarding its virtual environment, including a comprehensive set of the most used assets. To do so, Kim's theoretical methodologies (Kim, 2020) were applied to digital games to find out if it is possible to adapt these methodologies to various types of games. Since the research assembles the elements of the existing digital games, reverse engineering is used to segregate the games into their components. In our previous studies, we classified all the Steam games with the education tag based on the same methodology (Afshar et al., 2022) and data mined all the historical Steam games (Eshaghi et al., 2023); this time, we selected ten digital games for reverse engineering. In the game selection part, we used the IGN database, which is released as the top 100 video games of all time (IGN, 2021). In this list, we randomly selected the games published after 2010, regardless of their platform, to include any device's recent games. The other criterion for choosing the games was the amount of their focus on the virtual environment part of the game because of the research's target.

The research includes digital games with different classification codes based on Kim's game classification methodology to include various types of games in the pool. However, the similarities in the codes will be discussed in the continuation of the paper. This variation enables us to gather as much varied information as possible. Based on the mentioned principles, we selected ten games, given in Table 1, and provided their release date, developer(s), and classification code. For the reverse engineering of the selected games, the research considered each game's first level and tutorial to be played. Because they are places for beginners, and logically, we could assume that the designers put the most effort into them.

TABLE 1. List of Reversed Engineered Games.

#	Game Title	Release Date	Classification	Developer(s)
1	Journey	2012	GR33FP	Thatgamecompany, Santa Monica Studio, Tricky Pixels
2	Diablo III	2012	GR32SP	Blizzard Entertainment
3	Borderlands 2	2012	GR33CP	Gearbox Software, Aspyr, Aspyr (Mac)
4	Grand Theft Auto V	2013	MR33FP	Rockstar Games, Rockstar North, MORE
5	The Last of Us Remastered	2014	SR33CP	Naughty Dog
6	The Witcher 3: Wild Hunt - Game of the Year Edition	2015	SR33FP	CD Projekt, CD Projekt RED
7	Inside	2016	SR32LP	Playdead
8	Divinity: Original Sin II	2017	GR32CP	Larian Studios, Elverils
9	Fortnite	2017	MG33FA	Epic Games, People Can Fly
10	Red Dead Redemption 2	2018	GR33FP	Rockstar Games, Rockstar North

In the second stage, we classified all the elements in the games to the natural environment, artificial environment, story, and media layers. To be precise, it would have been better if we could approach the raw data of the games and count the number of assets and effects. However, since these data are protected as the developers' property and it was not possible to approach them, we took four screenshots of each game's first level for doing such a classification and counted the assets manually. We focused on the parts with the most available elements while taking the screenshots. Then we signed all the visible elements in the scene and defined codes for them based on the game's title and its layer. Afterward, we prepared a comprehensive table including the layer, category, asset code, type, name, interaction, detail, and the image file number for each game's assets. Subsequently, the number of assets in each level and their characteristics were analyzed. Table 2 demonstrates a brief asset list of ten reverse-engineered games, and Table 3 shows the number of assets in each layer.

TABLE 2. Brief Asset List of The Ten Selected Games.

Layer Name	**Asset Types**
Natural Environment Layer	Shrub, Paving, Water, Area, Object, Ruined, Grass, Flower, Tree, Underbrush, Hill, Moon, River, Mountain, Area, Sky
Artificial Environment Layer	Building, NPC, Fire, Human, Object, Smoke, Car, Tower, Road
Media Layer	Sound, Video, Viewpoint
Story Layer	Sound, Video

TABLE 3. The Number and Percentage of Assets in Each Layer of All Games (Dark Grey Columns Demonstrate the Most Assets, and the Light Grey the Least).

#	Game Title	Classification	Number and percentage of assets in each layer							
			Natural Environment Layer		*Artificial Environment Layer*		*Media Layer*		*Story Layer*	
			Number	*Percentage*	*Number*	*Percentage*	*Number*	*Percentage*	*Number*	*Percentage*
1	Journey	GR33FP	9	21.4%	17	40.5%	13	31.0%	3	7.1%
2	Diablo III	GR32SP	35	35.7%	28	28.6%	21	21.4%	14	14.3%
3	Borderlands 2	GR33CP	8	14.5%	35	63.6%	8	14.5%	4	7.3%
4	Grand Theft Auto V	MR33FP	16	23.9%	33	49.3%	14	20.9%	4	6.0%
5	The Last of Us Remastered	SR33CP	8	16.3%	21	42.9%	14	28.6%	6	12.2%
6	The Witcher 3: Wild Hunt - Game of the Year Edition	SR33FP	44	47.3%	15	16.1%	23	24.7%	11	11.8%
7	Inside	SR32LP	33	45.8%	12	16.7%	20	27.8%	7	9.7%
8	Divinity: Original Sin II	GR32CP	12	12.9%	60	64.5%	14	15.1%	7	7.5%
9	Fortnite	MG33FA	33	41.8%	12	15.2%	23	29.1%	11	13.9%
10	Red Dead Redemption 2	GR33FP	28	28.9%	22	22.7%	19	29.9%	21	18.6%

Notably, the randomly selected games have a similar digit in their codes. According to Kim, the code's second digit expresses the story type of the game as representing or generating. As Table 1 depicts, nine of ten played games have an R code in their second digit, while only Fortnite (2017) has a G code in this digit. To explain more in detail, the paper provides the coded screenshots of The Last of Us Remastered (2014) as a sample of a representing game and Fortnite (2017) as a generating one (Figure 2 and Figure 3). Additionally, Figure 4 shows their asset ratio in each layer, demonstrating the focus of each game's elements on a specific layer. For instance, the Last of Us Remastered (2014) analysis depicts that the assets are focused mainly on the artificial environment layer, with 42.9%, and the Fortnite (2017) game focused its assets on the natural environment layer, with 41.8%.

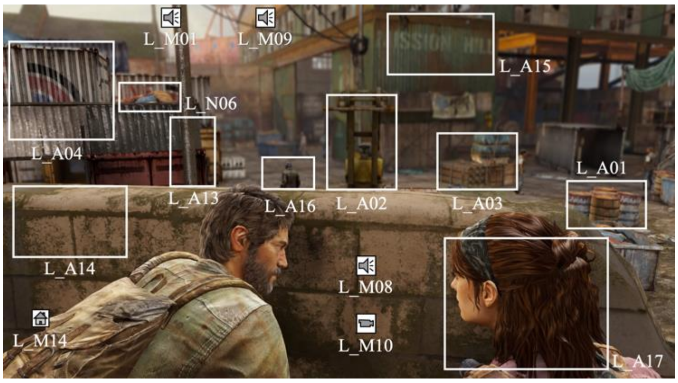

Figure 2. Sample of a coded screenshot of The Last of Us Remastered game (2014)

Figure 3. Sample of a coded screenshot of The Fortnite game (2017)

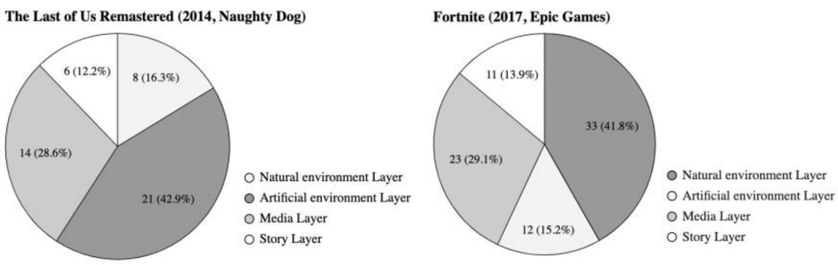

Figure 4. Asset Ratio Sample

Concluding these data for all ten games leads us to the point that the story layer consists of the least number of assets among the others. Even considering the game's background environment, which is an abandoned urbanscape, we can assume that game developers paid more attention to the natural and artificial layers. However, the ratio of the games shows that the significant majority of current digital games have a storytelling theme. This suggests a potential disconnect between the narrative intent and the actual asset allocation in game development.

4. Conclusion

To conclude, the digital game industry, a realm of innovation and creativity, currently faces a discernible gap in its methodological approach, especially when it comes to the design of virtual environments. Kim's pioneering proposition, which introduces a digital game classification and design methodology inspired by architecture, landscape architecture, and urban planning, offers a fresh and potentially transformative perspective. This research, in its essence, seeks to bridge the theoretical with the practical, aiming to discern the applicability of Kim's methodologies across a diverse spectrum of games.

Through an exhaustive process of playing and reverse engineering a curated selection of ten games, we've amassed a comprehensive data set. Developed with a meticulous coding system, this set categorizes the myriad assets employed within these games. However, the constraints of this study, particularly the manual counting of assets due to the inaccessibility of raw game data, underscore the challenges inherent in such research. Furthermore, the limited sample size of games analyzed, suggests that for a more robust and definitive conclusion, a broader and more diverse selection of games would be instrumental.

Our findings, while preliminary, are illuminating. They not only shed light on prevailing industry trends but also highlight its glaring gaps. It's particularly noteworthy that while the majority of contemporary games are steeped in narrative-driven themes, there's a conspicuous absence of assets dedicated to the story layer. This reliance on character dialogues and in-game texts for narrative delivery, while effective for some, can potentially alienate a segment of players, leading to a diminished gaming experience. Moreover, such an approach inadvertently creates linguistic barriers, narrowing the game's appeal to those proficient in specific languages.

Our research underscores the potential benefits of enriching the story layer with a diverse array of assets, thereby fostering a more immersive and linguistically inclusive gaming experience. The broader implications of this are profound, suggesting a shift towards games that are not only more engaging but also more globally accessible. By integrating Kim's digital game design methodology, there's an opportunity to usher in a new era of game design, one that's holistic and considers every facet of the virtual environment.

Furthermore, the synthesis of our data set with Kim's methodologies lays the groundwork for future innovations, particularly the potential development of a specialized tool tailored for the digital game industry. Such a tool could be revolutionary, equipping professionals with the means to allocate equitable attention to all game layers, thereby fostering the creation of more balanced and holistic digital games. This, in turn, could streamline the game development process, ensuring optimal utilization of labor, time, and financial resources.

In the grand tapestry of game design, the threads of innovation, methodology, and inclusivity must intertwine. As the industry continues to evolve, it's imperative to embrace methodologies like Kim's, ensuring that games of the future are not only technologically advanced but also rich in narrative depth and universally accessible. The horizon of game design beckons, and with the right tools and approaches, the industry stands on the cusp of a renaissance.

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FOSTERING CULTURAL HERITAGE AWARENESS THROUGH GAME ELEMENTS

Route Design for Mixed Reality Experience of the Yedikule Fortress

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Abstract. Cultural heritage sites, with their diverse architectural spaces, offer visitors unique opportunities to engage with their environmental and structural features. This paper presents the initial phase of a broader research endeavor focused on conveying cultural and historical information by integrating game elements within the context of cultural heritage. The primary objective of this study is to design a comprehensive route for the Yedikule Fortress, highlighting its key attractions while emphasizing its cultural and historical significance. During the design phase, we began by compiling and evaluating data concerning visitors' activities and points of interest within the social media and the physical space of the site. We then integrated this information with historical data, establishing connections between prominent events and specific locations. This paper will discuss the issues to be considered and the method to design a route of game-based MR experience in cultural heritage areas. This paper will discuss the critical considerations and methodology employed to create a route for a game-based Mixed-Reality (MR) experience in cultural heritage areas.

Keywords: *Route Design, Cultural Heritage, Mixed Reality, Gamification, Cultural Awareness*

ملخص. توفر مواقع التراث الثقافي، بمساحاتها المعمارية المتنوعة، للزوار فرصًا فريدة للتفاعل مع سماتها البيئية والهيكلية. تعرض هذه الورقة المرحلة الأولية من مسعى بحثي أوسع يركز على نقل المعلومات الثقافية والتاريخية من خلال دمج عناصر اللعبة في سياق التراث الثقافي. ويكمن الهدف الأساسي من هذه الدراسة في تصميم طريق شامل لقلعة

يديكولي، مع تسليط الضوء على مناطق الجذب الرئيسية مع التأكيد على أهميتها الثقافية والتاريخية. خلال مرحلة التصميم، بدأنا بتجميع وتقييم البيانات المتعلقة بأنشطة الزوار ونقاط الاهتمام داخل وسائل التواصل الاجتماعي والمساحة الفعلية للموقع. ثم قمنا بدمج هذه المعلومات مع البيانات التاريخية، وإنشاء روابط بين الأحداث البارزة ومواقع محددة. تناقش هذه الورقة البحثية القضايا التي يجب مراعاتها وطريقة تصميم مسار لتجربة الواقع المختلط القائمة على الألعاب في مناطق التراث الثقافي. تناقش هذه الورقة الاعتبارات الهامة والمنهجية المستخدمة لإنشاء طريق لتجربة الواقع المختلط (MR) القائمة على الألعاب في مناطق التراث الثقافي.

الكلمات المفتاحية: *تصميم المسار، التراث الثقافي، الواقع المختلط، اللعب، الوعي الثقافي.*

1. Introduction

Cultural heritage sites, with their diverse architectural spaces, offer visitors unique opportunities to interact with the environmental and structural features that define our shared history. Individuals must be aware, educated, and conscious of the need to protect these cultural heritage sites. To foster a greater appreciation of heritage values within society, it is essential to ensure that these areas are perceived, valued and presented accurately (Goud, S., Lombardo, V.,2022). In pursuit of this goal, ICOMOS issued the 'Cultural Heritage Perception and Presentation Charter' in 2008. To enhance visitors' experiences and deepen their understanding and appreciation of these sites, various interfaces, media, tools and/or approaches have been explored, including Mixed Reality (MR) technology, Augmented Reality (AR), and Virtual Reality (VR) (referred to as spatial computing technologies in this paper) combined with game elements. Spatial computing technologies, MR in particular, influences our perceptions by presenting interactable virtual objects as an augmented layer integrated into the physical world. Harnessing this capability, the use of MR for designing multi-layered narratives for heritage sites has garnered increasing attention in recent years.

In the discipline of heritage conservation, the concept of ‘multi-layered’ implies a cultural heritage shaped by the architectural reflections of civilizations dominating a place throughout its historical evolution. To put it more clearly, the physical and cultural unity of a heritage place emerges from the contributions of different societies over the centuries. This unity is evident in the physical pattern, both horizontally and vertically (as defined by Karabağ, 2008, p. 20). Horizontal layering refers to the connection between existing cultural assets accessible in our physical environment, while vertical layering pertains to the linkages with underground remains, which fall under the domain of archaeology. In cities like Istanbul, boasting a history spanning thousands of years, approaching multi-layered historical textures and interpreting heritage value while preserving its essence is utmost importance. During visits to historical areas in Istanbul, advanced spatial computing technologies can offer enriched experiences through a digital/electronic layer (referred to as the e-layer) which contains informative and sometimes entertainment elements. With this in mind, we have designed a route within Yedikule Fortress where the heritage aspects of this ancient structure can be experienced using the game elements (e.g. jigsaw puzzles, object collection) and fact cards that inform and entertain users.

This paper presents the initial phase of a comprehensive research project that deals with conveying cultural and historical information through the integration of game elements, and as a future study we will explore users' spatial cognition within the context of cultural heritage. The research encompasses multiple phases, which include site documentation using photogrammetry (see Sancak et al., 2023), designing a cultural route with game elements, fact cards and narrative (as presented in this paper) developing interface elements for spatial computing technology (specifically, HoloLens 2) and conducting user studies with various technology settings.

In this paper, we present the design of a cultural route that involves a field research tour, historical narrative research of Yedikule, analysis of social media content, and two separate workshops. The cultural route was then tested with six individuals, and necessary adjustments were made based on their feedback. This designed route consists of **nodes and links,** accompanied by an aural narrative that elucidates the story of the place. Researches has demonstrated that incorporating storytelling elements and narration can heighten emotional involvement, improve learning about the location, and aid in remembering heritage content (Bellucci et al., 2014; Pietroni et al., 2018). Based on that, we argue that the integration of game elements and aural narration during a visit to a historic settlement would create an enhanced e-layer, enriching the understanding and appreciation of its heritage value.

2. Game Studies and Spatial Computing Technologies in Heritage Context

Over the past ten years, gamification and serious games have received a lot of attention in cultural heritage (Foni et al., 2010). According to a thematic bibliometric analysis based on the Elsevier Scopus database, in the field of game and cultural heritage (257 articles included: game AND 'cultural heritage'), 'app development', 'technology', 'game experience', 'serious games', 'knowledge' and 'museum' are the most frequently encountered concepts; and the concepts of 'learning' and 'protection of cultural heritage' were less frequently encountered keywords (see Karahan and Gül, 2021 for more detail). Studies in the intersection of game and cultural heritage focused on mainly VR and AR environments, game experience and storytelling (Dow et al., 2005; Kim et al., 2015; Volkmar et al., 2018) and historical heritage awareness (Volkmar, et al., 2018; Kim, et al., 2015).

In the fields of cultural heritage, archeology and museology, games have been dealt with in various ways. For example, Mortara et al., (2014), examining serious games in the cultural field; revealed the complex relationships of concepts such as gender, usage area, technological solutions and learning efficiency. The main goal of serious games in those examples is to facilitate players' experiential learning. They provide users with a fun way to accomplish learning goals, such as familiarizing themselves with cultural heritage subjects and stimulating their interest in them (Mariotti, 2020). More and more research are being conducted in various subjects and at all educational levels on game-based learning, a component of serious games (Vaz de Carvalho et al., 2013). For example, a composite serious Game featuring the Stoa of Attalos, a significant building in the Ancient Athens Agora, has been released by Skamantzari et al. (2017). The game uses 3D models produced primarily by automated image-based modeling methods. These games are focused on experiential interaction with digital heritage (Malegiannaki, 2017), informing the visitors and enriching and entertaining the tour (Doulamis et al., 2012; Coenen et al., 2013), making architectural spaces experienced by supporting the impulses of interaction, exploration and criticism (Aydın, et al., 2014; Fanini and Pagano, 2015), increasing the public's interest in cultural heritage and raising awareness (Affleck and Kvan, 2005; Volkmar et al., 2018), and support learning in the field of history and heritage.

Among these studies, our research holds unique value as it offers an experiential approach to exploring historical heritage through a thoughtfully designed route that incorporates game elements, while also evaluating users' spatial cognition and perception. The incorporation of gaming concepts in this study aims to strengthen the spatial relationship with the heritage context and narrative, motivating and engaging users during their sightseeing experience. However, it's important to note that the game elements is not solely developed for entertainment purposes; rather, it is intended to enhance the understanding and appreciation of the cultural heritage along the route. In this study, we emphasize the need to design game elements in a way that complements and respects the historical value of the heritage sites experienced on the cultural route. By focusing on landmarks, route planning, and mental maps—elements commonly discussed in spatial cognition literature—we ensure that the game elements are intricately tied to the significance of the heritage sites, leaving a lasting impression on users after their experience.

3. Route Design in Yedikule Fortress

In a cultural heritage site, the route that is composed of tangible elements of cultural significance (see Routes as a Part of Our Cultural Heritage" meeting of UNESCO and ICOMOS in 1994, as cited in Karataş 2011:13) can play a very critical role in visitors' experience and comprehension of the site (Durusoy, 2014). Within the scope of this research, the restructuring approach has been taken as a basis in the process of developing the cultural route of Yedikule Fortress. Some of the principles of heritage interpretation are applied here (see Tilden 1957) e.g.:

- Provoke: attention, curiosity and interest.
- Relate: to the everyday life of your visitors.
- Reveal: the main concept or theme through some creative or unusual viewpoint.
- Address the Whole: make sure your program relates to your main Project Theme.
- Message unity: use the correct supporting elements in your program to illustrate your theme or main concept.

Based on those principles, there were several factors that we have to take into consideration in our effort to design a cultural route that could be experienced with an e-layer containing heritage interpretation with fact cards - aural narrative, interface and game elements.

First and foremost, we have to make sure to provide the visitors with accurate information about the history of the site and its cultural and historical significance. We have to optimize the amount of information to convey in accordance with the possible amount of time visitors like to spend at site and to an extent that would not exhaust the visitors. We have to understand the potentials and limitations of our site and the profile of its visitors, for instance, identify the areas that are open to visit or can be viewed from currently accessible areas, the elements of the site/city that can be seen from them, areas/components and facts that attract the visitors most, among others. While doing so, we have to seek potential content for game design, identify what could be the objective and respective scope of the games given the current capabilities of the tools we will use, when and where they could best be incorporated into the visiting experience.

With its 1600-year history, Yedikule Fortress, 22400 m^2 heritage site, includes many layers from the Byzantine Empire to the Ottoman Empire, being a dungeon to the royal treasury, and continues as a museum until today. This multi-layered structure makes the Fortress an important example of urban cultural heritage. This historical fortress, which gave its name to the Yedikule district of Istanbul, has a pentagonal form surrounded by seven towers. The fortress has been significantly damaged throughout history and has been repaired at various times. Only six of the towers have survived; These towers can be listed as Inscriptions Tower (The Dungeon Tower), Cannon Tower, Young Osman Tower (South Pylon), Armory Tower (North Pylon), Ahmet III. Tower (Pastorama Tower) and Treasure Tower. Given its size, it normally takes a visitor around 90 minutes just to walk to and step foot on the spaces of the key attractions on the site without any stop for a rest. The current guided tour on site takes around 1 hour with the guide speaking for around 75 minutes.

Taking the above factors into consideration and in the light of the extensiveness of the history to share and the size of the site, we carried out several methodologies in parallel with each informing the others in our effort to design the route. We visited the site several times, initially with the guidance of an expert in its history, to develop a comprehensive understanding of its various components, potentials, challenges and current visit patterns. We observed the visitors' behaviors on site, the paths they follow, the areas they visit to identify the focal points on site. At the same time, we also researched social media to identify the aspects of the Yedikule Fortress that attract the most visitors today. We chose Instagram as the social media platform for this study due to its unique focus on visual content sharing. We analyzed public photo shares from November 2022 to a year prior in six different location tags related to Yedikule: "Yedikule Zindanları," "Yedikule Hisari," "Yedikule," "Yedikule Fortress," "Porta Aurea (Constantinopolis)," and "Istanbul 7 Kule Zindanları". For this purpose, we identified approximately 300 public images for analysis. In these photographs, we not only captured the frequently photographed parts of the castle but also find about key landmarks in the area that aligned with our observations. Our findings revealed that the most photographed areas were the views of the courtyard and the Marmara Sea from the terrace of the Golden Gate, the Golden Gate itself, and the Inscriptions Tower, as shown in Figure 1.

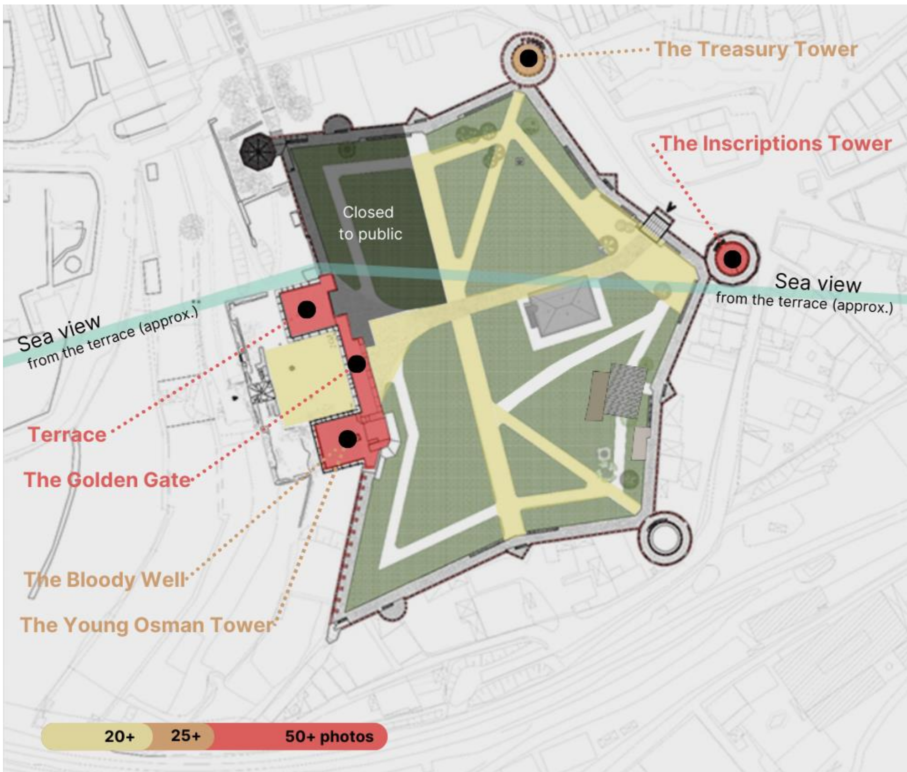

Figure 1: Yedikule Fortress Instagram Image Search Results

Following these, the Young Osman Tower, the Bloody Well (Kanlı Kuyu) within it, and the Treasury Tower were also recognized as significant points of visitor interest. Based on our observations on site and in social media research, we were able to identify the focal points at our site and the aspects that visitors find most intriguing about the Yedikule Fortress, thus the areas that should be included in our route and the aspects that we can highlight in the context of the guide and/or through the games towards creating a more engaging and satisfying visitor experience.

In parallel to our analyses on-site and social media, we conducted in-depth literature research to access accurate information about the history of Yedikule Fortress, and identify the set of key events in its history. We conducted a series of brainstorming workshops (as seen in Figure 2) with the participation of researchers; we overlapped all the data we collected up to that point by using historical narratives, maps, and engravings. During the workshop, we made key decisions regarding the aspects of the field we should emphasize, the historical figures that would enhance our narrative, and the game elements we could incorporate.

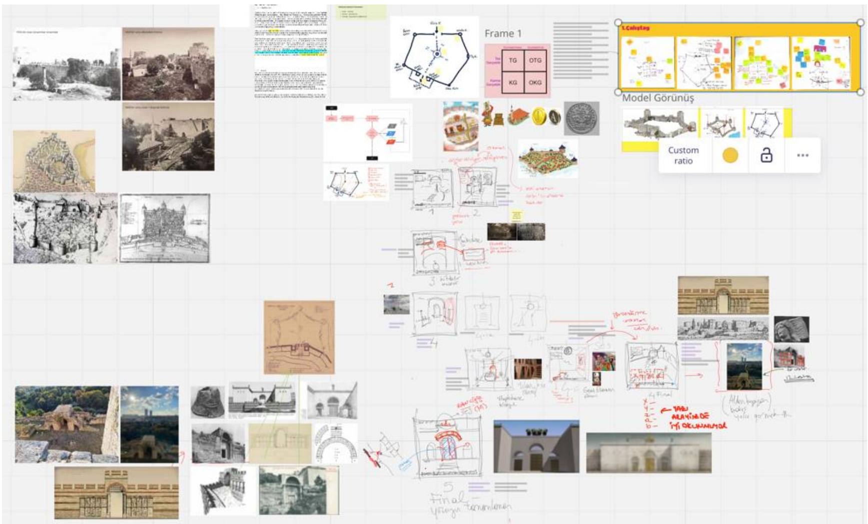

Figure 2. Screenshot of Miro board of the workshops; old maps, engravings, narratives and reconstruction drawings were used as resources in the workshop.

Through these efforts, we were able to (1) identify the focal points/areas to be visited during the tour on site, which we refer to as **nodes** in our diagrams (Figure 3), (2) design a path comprising segments, which we refer to as **links** in our diagrams, that connect these nodes, a path that visitors will follow in a certain direction to reach at or pass through these nodes, (3) compose a series of narratives that will be shared with the visitors at these nodes or while going from one node to another and (4) develop an initial design for the mini games, identifying the timing, place and the components in conjunction with the content of the corresponding narratives by working closely with historians and experts to ensure historical accuracy and cultural sensitivity. This way, we could establish an enhanced route that unfolds events based on the places rather than their chronological order.

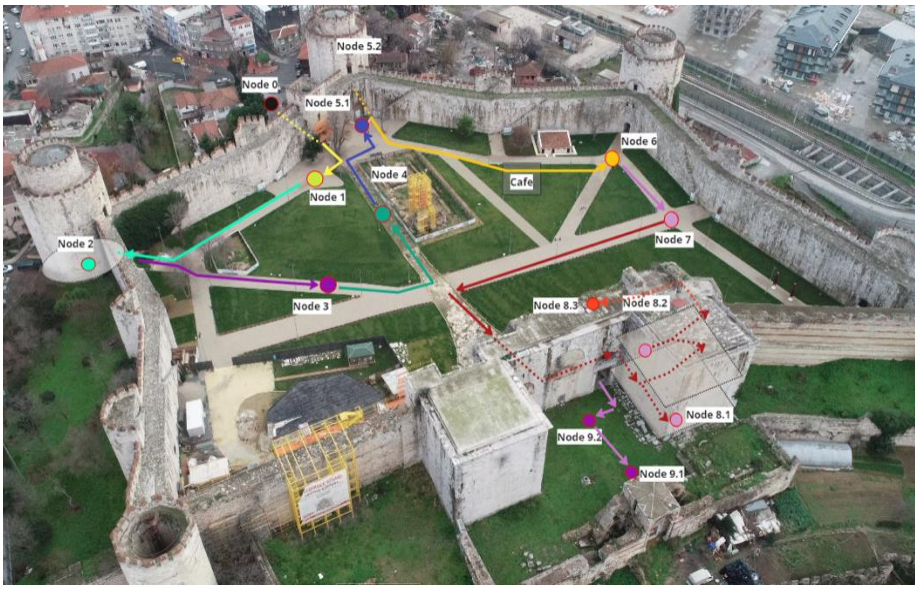

Figure 3. The aerial view of the Yedikule Fortress. Node 0 (entrance), Node 1(Under the tree, banks), Node 2 (Treasury Tower), Node 3(Closer view to III. Ahmet Tower) , Node 4 (In front of the mosque, stairs), Node 5.1 (Inscription Tower front door), Node 5.2 (Inside Inscription Tower), Node 6 (In front of Cannon Tower), Node 7 (In front of Flag Tower), Node 8.1 (Bloody Well), Node 8.2 (Room of Young Osman), Node 8.3 (Golden Gate terrace, looking towards the courtyard), Node 9.1 (Inscriptions), Node 9.2 (Looking behind the Golden Gate)

Following our path design, we used an AI voice generator (https://play.ht/) to translate the narratives to speech and prepare audio files to test the design on-site. We initially visited the site to evaluate the route design from the perspective of the walkability of the path in the foreseen amount of time, the views to be captured while following the path, the relation between views and the content, and the timing and duration of the narratives. Modifying the design based on our evaluations and observations, we then carried out three sets of pilot studies with participants to examine it at various levels and make the necessary modifications on the route design. Following each user's experience, we made corrections to the route, until we detected no problems with the route, eventually repeating the pilot study 6 times. Among others, the data we collected in these pilots included the timing of the narratives, the time it takes participants to walk between nodes, whether the participants were able to identify the nodes based on their descriptions in speech and thus, whether they seamlessly followed the path or diverged from it, the extent at which they learned about the layout of the site (as collected through a sketch map the participants drew upon completion of the study, a total of 6, as shown in Figure 4), participants resulting opinions about the site and its historical significance (as collected through a questionnaire) and about their overall experience (as learned about through open ended interviews conducted with the participants after completing the tour).

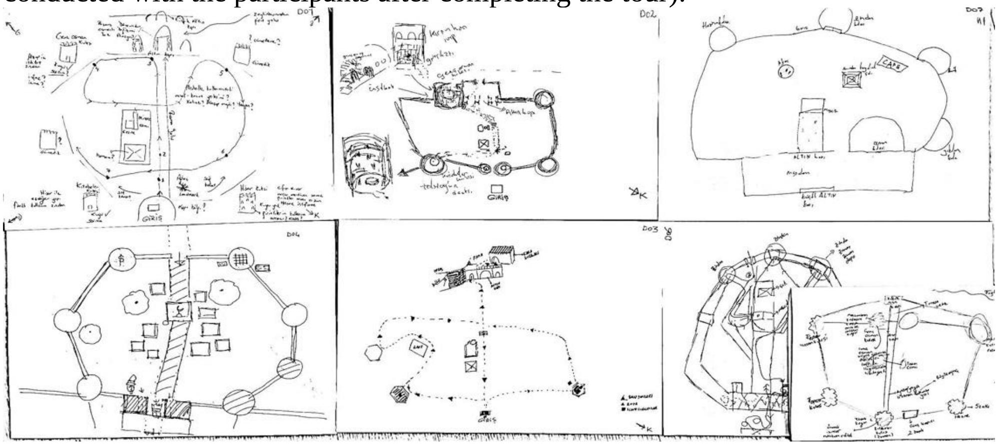

Figure 4. The pilot experiment participants' drawings indicate the travel route and items they recalled.

4. Interpretation of Heritage and Game Elements for Mix Reality

In the present-day context of heritage conservation, the role of heritage interpretation and expression has gained increasing significance, evolving from an 'auxiliary element' to become a fundamental aspect (Töre, 2017). Contemporary conservation practices no longer solely focus on repairing, protecting, and re-functionalizing cultural heritage sites; instead, there is a growing recognition of the need for comprehensive communication and perception plans (see Burra Charter, 2013). It is now considered vital to preserve the physical aspects of cultural heritage and design and implement strategies that engage and connect with visitors on a profound level.

In this study, we emphasize the significance of public participation in heritage protection as an integral part of the process to enhance the level of awareness and appreciation. We have developed engaging multimedia elements such as mini games, animations and fact cards strategically placed along the route to captivate visitors' attention and motivate them to explore the heritage site.

Two different travel-kits for the visitors are designed: the first one is a physical kit featuring a jigsaw puzzle printed on a paper board, which incorporates historical information, the second one is a digital travel kit with an e-layer. The e-layer includes the same route and historical information as the physical kit and interactive mini games, animations and experiences leveraging spatial computing technology, specifically MR- HoloLens 2, as depicted in Figure 5. The focus of this paper is not on the user studies of these different settings, as it will the subject of a future study.

What we have learned from the pilot studies is the strong interest generated by the mosque and the old settlement located in the middle of the courtyard (which does not exist today). Additionally, the historical significance of two towers and the Golden Gate captured considerable attention. Thus, these points of interests are marked as **nodes** in our route design. In the general game narrative, players will collect gold coins called '*Sikke'* an old Ottoman gold coin, at each **node**. The aural narrative will accompany and lead to **nodes** where players will complete tasks such as solving a jigsaw puzzle or locating specific items.

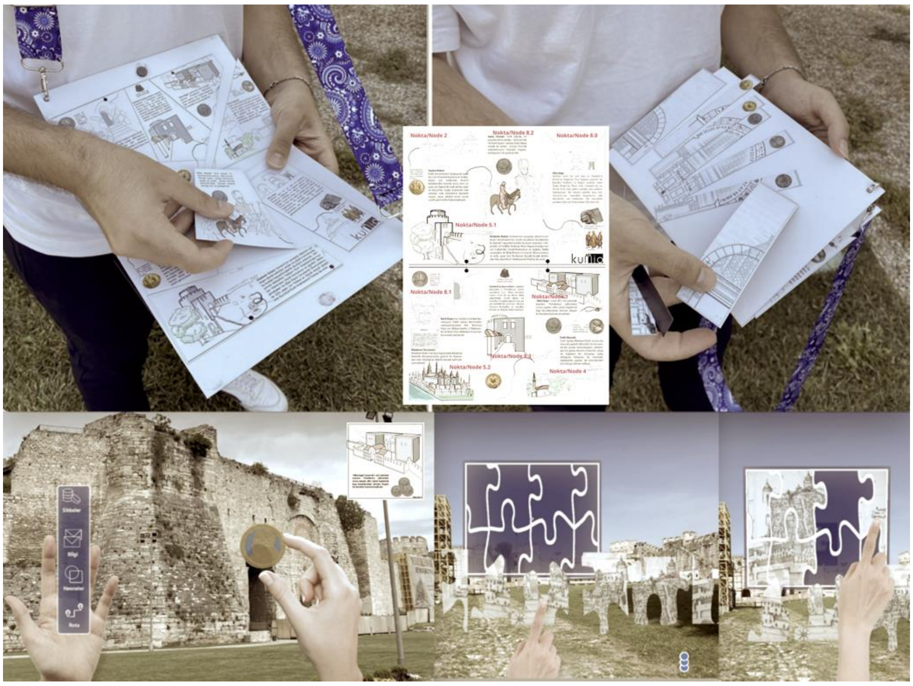

Figure 5. Different jigsaw puzzles as game elements at certain positions (Node 4 and 5.2), one of that is, an Ottoman miniature showing the neighborhood located in the middle of the courtyard. The route experiencing setting has two folds: one is the visit with the printed materials (top), and the second is the visit with MR technology (HoloLens 2 screen bottom).

Upon solving a puzzle at a designated position, a *Sikke* will be collected (as shown in Figure 5 bottom-right). In the printed version, a strip of papers featuring a *Sikke* image will be collected (as shown in Figure 5 top-right). In the MR version, a digital S*ikke* will be rendered within the physical world, allowing users to interact with and collect it as if it is physically present, despite its virtual nature, as shown in Figure 5 bottom-left. After acquiring several S*ikkes*, players will receive a final clue that will unlock the secret of the Golden Gate, presented as an ancient inscription puzzle.

The actions, such as mini-games or object collection taking place within the **nodes**, and the **links** between **nodes**, as previously mentioned, are carefully designed in relation to the historical use of the space or events that occurred in the past. For instance, nodes featuring locations like the Bloody Well and Young Osman's room are explained by reconstructing how these spaces were utilized during specific periods and the events that transpired within them. To ensure the overall message is effectively conveyed, we meticulously curated the information provided to keep the visitor engaged with the place. The observations and the initial results from the pilot study indicate that places and events can be readily recalled, and participants expressed satisfaction with the overall experience. Additionally, all participants strongly desired to learn more about the place and appreciate its significance and value.

We reaffirmed that even when a visual reconstruction is undertaken by an expert artist, architect or computer technician, it should be based on a systematic and detailed analysis of the environment, incorporating written, oral, graphic or photographic information, along with archaeological, architectural and historical data (as emphasized by Bendicho et al, 2017). In the digital domain, effective communication with heritage context and interpreting historical events require a multi-disciplinary teamwork approach.

5. Concluding Remarks

In conclusion, this research represents an innovative integration of game, visitor engagement, and spatial computing technology within the historical context of the Yedikule Fortress. By combining heritage interpretation principles with advanced spatial computing technologies, particularly HoloLens 2, a comprehensive understanding of the 1600-year history of Yedikule Fortress has been achieved, resulting in an engaging and immersive experience for visitors.

In designing a game-based cultural route, several key factors emerged to enhance the user experience. Primarily, the narration should be rooted in the places and events that have historically taken place on the locations along the route, thus **nodes** and **links** should be carefully studied. This historical storytelling adds depth and context to the user's tour, promoting a deeper appreciation for the heritage sites. In addition, incorporating simple games that are intricately tied to the history and cultural significance of the tangible and intangible heritage values can notably engage and captivate users during their tour. Such gamification has the potential of not only enhancing enjoyment but also to facilitate an immersive learning experience. Moreover, the usability of the interface (both printed and digital) is of utmost importance; it should be easy to navigate and quick to grasp, allowing users to fully immerse themselves in the cultural journey without any technical obstacles. Lastly, the e-layer including the activities along the route should be designed to instill curiosity and a thirst for comprehension, motivating users to seek further information about the places they encounter. By stirring this desire for learning, the cultural route may become a delightful experience and an enriching educational opportunity.

As the research continues, it remains vital to consider both the tangible and intangible elements of the site, exploring how the physical and digital realms interact harmoniously. Ultimately, this research aims to contribute to a deeper appreciation and understanding of cultural heritage, offering visitors an enriched experience that intertwines technology, historical narratives, and the profound legacy of Yedikule Fortress. The main experiments with participants are still ongoing, and the next stage involves completing user experiments to examine further research questions related to spatial cognition and heritage awareness.

Acknowledgments

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ROLE-PLAYING GAMES AND NARRATIVE ARCHITECTURE IN DESIGN METHODS: A SYSTEMATIC REVIEW

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Abstract. This paper reviews existing research on the teaching of narrative architectural design and the creation of role-playing games (RPGs), with an interdisciplinary connection between them. The paper conducts a systematic review and analysis of 27 academic papers. These articles are selected from the academic database "Connected Papers" using the keywords "narrative architecture, architectural design teaching, narrative story, RPG creation." This database employs natural language processing technology to analyze the links and influencing factors among articles in different disciplines. We then performed a key review of a selection of 5 papers addressing the interdisciplinary application between architectural design teaching and RPG creation. The key papers content includes a discussion of the problems and solutions in the creation methods of narrative architecture and RPGs, aiming to crystalize the defects and advantages of both approaches. Our findings summarize the process of materializing narrative content in two different creative industries, discussing the challenges they face and the existing solutions. Drawing from the narrative architectural design teaching effects and RPG creation results presented in the literature, this paper summarizes the advantages of both practices. This allows us to provide a summary of the current industry progress and identify possible research gaps based on the present status of interdisciplinary applications between the two.

Keywords: *Narrative architecture, Role-playing-game, Narrative story, Architectural design teaching.*

ملخص. تستعرض هذه الورقة الأبحاث الموجودة حول تدريس التصميم المعماري السردي مع وجود علاقة متعددة التخصصات بينهما .تجري ،(RPGs) وإنشاء ألعاب تمثيل الأدوار الورقة مراجعة وتحليل منهجي لـ 27 ورقة أكاديمية .تم اختيار هذه المقالات من قاعدة باستخدام الكلمات الرئيسية "الهندسة المعمارية "Connected Papers" البيانات الأكاديمية السردية، تدريس التصميم المعماري، القصة السردية، إنشاء آر بي جي ."تستخدم قاعدة البيانات هذه تكنولوجيا معالجة اللغة الطبيعية لتحليل الروابط والعوامل المؤثرة بين المقالات في مختلف التخصصات .قمنا بعد ذلك بإجراء مراجعة أساسية لمجموعة مختارة من 5 أوراق تتناول التطبيق متعدد التخصصات بين تدريس التصميم المعماري وإنشاء ألعاب تقمص الأدوار .يتضمن محتوى الأوراق الرئيسية مناقشة المشاكل والحلول في أساليب إنشاء العمارة السردية وألعاب تقمص الأدوار، بهدف بلورة عيوب ومزايا كلا النهجين .تلخص النتائج التي توصلنا إليها عملية تجسيد المحتوى السردي في صناعتين إبداعيتين مختلفتين، ومناقشة التحديات التي تواجههما والحلول الحالية .بالاعتماد على تأثيرات تدريس التصميم المعماري السردي ونتائج إنشاء آر بي جي المقدمة في الأدبيات، تلخص هذه الورقة مزايا كلتا الممارستين .يتيح لنا ذلك تقديم ملخص للتقدم الحالي في الصناعة وتحديد الفجوات البحثية المحتملة بناءً على الوضع الحالي للتطبيقات متعددة التخصصات بين الاثنين.

الكلمات المفتاحية: العمارة السردية، لعبة تمثيل الأدوار، القصة السردية، تدريس التصميم المعماري.

1. Introduction

Narrative architecture entails architects conveying design concepts through storytelling, formulating architectural scenarios and spatial layouts rooted in these narratives (Bleeckere and Gerards, 2017). In architectural design education, the fundamental steps of narrative architectural design encompass eight components: Narrative Concept, Spatial Design, Interactive Design, Contextual Integration, and Iteration and Feedback (Coates, 2012). Architects address architectural elements, spatial arrangement, sensory experiences, and interactions within spaces throughout the spatial design and interactive design phases. During the contextual integration phase, architects meticulously assess the coherence between their preceding narrative designs and the site's context (Childs, 2008). However, architects' established design logic during the spatial and interaction design stages might face challenges in the Contextual Integration phase, leading to confusion and influencing overall design control, particularly for novice practitioners (Soliman, 2017). Certain architectural designers mitigate substantial divergences between phases by concurrently conducting coherence checks of the context integration phase during the formulation of the initial two phases (Psarra, 2009). Yet, this approach demands for logical thinking, introducing fresh obstacles for architects and architecture students lacking design experience (Nazidizaji *et al.*, 2015).

The objective of RPG creation is to establish an immersive sense for conveying narrative content by materializing it (Skolnick, 2014). In the early stages, RPG creation relied on the artistic abilities of planners. Insufficient personnel experience and skill resulted in many RPGs encountering issues with the lack of internal coherence between background stories and scene content (Brown and Cairns, 2004). To address these challenges, the gaming industry has developed an RPG creation approach that initially constructs the game's background world view and subsequently refines the storyline and constructs scenes in alignment with the overarching world view (Bethke, 2003). This creation method encompasses eight stages: Conceptualization, Pre-production, Art and Asset Creation, Programming and Game Implementation, Level Design and Content Creation, Playtesting and Iteration, Certification and Release, and Post-release Support (Petrillo *et al.*, 2009). Designers define the requisite game elements in the early phase, proceed to generate assets in subsequent stages, and employ these prepared assets for storytelling and scene design in the final phase (Aleem, Capretz and Ahmed, 2016b). This method empowers designers to identify their own requirements and consistently reinforce the game's background settings throughout the creative process, ensuring a strong correlation between physical content and narrative content, particularly for inexperienced novice designers (Reardon and Wright, 2021). The current RPG creation approach embodies a form of "experience design," seeking to engage multiple senses of the human body and comprehensively evoke player emotions through diverse sensory stimuli, with the aim of more effectively conveying narrative content (Reardon and Wright, 2021).

Both narrative architectural design teaching and RPG creation share the goal of crafting deeply immersive scene experiences that align with narrative content. Some scholars have initiated cross-disciplinary exploration, drawing insights from both fields. In RPG creation, architectural research outcomes, primarily rooted in interior decoration and building block composition, have been extensively referenced for designing interior scenes and architectural assemblies (Jenkins, 2004). However, within the realm of narrative architectural design education, there is notably less incorporation of RPG creation as a reference. A handful of universities have experimented with integrating elements of narrative story creation from RPGs into architectural design to enhance immersive design (Lim, 2013). Nevertheless, the considerable potential of RPGs, particularly in influencing player emotions through adept scene design to more effectively convey narrative content, remains relatively unexplored in terms of its applicability to narrative architecture. Exploring the "interplay between scene design and emotional expression" within well-crafted RPGs could yield insights into the correlation between architectural scenes and emotional evocation, proving invaluable for architecture students as they delve into narrative architectural design.

2. Review questions and aim

Through a review of existing research on narrative architecture and RPG creation methods, this paper explores the challenges and remedies within their creation processes, elucidating their respective shortcomings and advantages. Specifically, the paper addresses the following research questions:

> What aspects of RPG content creations methods, are most valuable for reference and research, to teach narrative architectural design?

3. Review methodology

Our systematic review method comprises four phases (Figure 1.). 1) Retrieving articles via the Connected Papers database, 2) Screening selected papers, 3) Classifying and analyzing each paper's content, and 4) Summarizing existing research content and identifying potential research gaps.

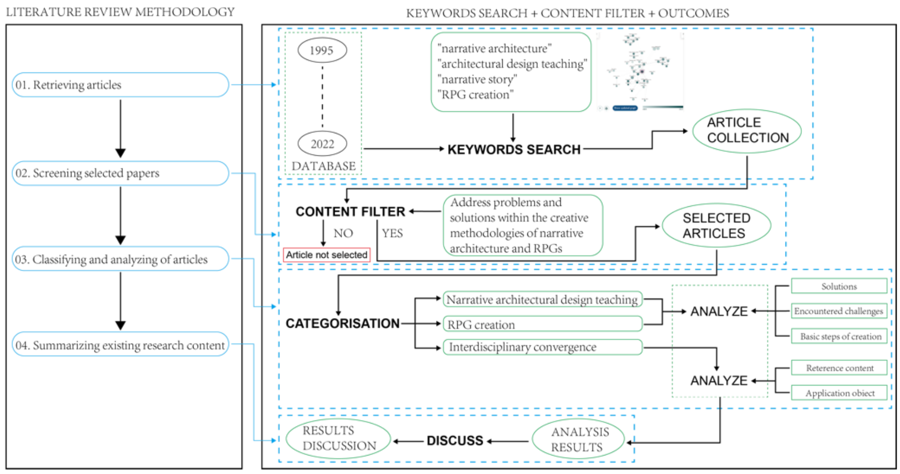

Figure 1. Literature Review Methodology

In the initial stages of our research, we utilized Connected Papers—an academic database recognized by numerous universities and academic institutions. This database uses an NLP technology, which uses language models decompose article and analyze keywords to perform article content analysis. We chose this database due to its emphasis on scrutinizing connections and influencing factors among articles across distinct disciplines, facilitating our exploration of interdisciplinary correlations between the two fields. The search keywords encompassed "narrative architecture, architectural design teaching, narrative story, RPG creation." Following the screening process, we identified 47 academic publications. In the subsequent phase, we refined the selection to 27 articles by excluding those that did not address problems and solutions within the creative methodologies of narrative architecture and RPGs. In the third phase of our literature review, we classified the 27 articles into categories: 1) Introduction to narrative architectural design teaching, 2) Introduction to RPG creation, and analyzed them based on: 1) Basic steps of creation, 2) Encountered challenges, and 3) Solutions. From this pool of 27 articles, this paper highlights 5 pieces of literature pertaining to the interdisciplinary convergence of architectural design teaching and RPG creation, elucidating the present industry progress. The analysis results revealed frequent occurrences of narrative architecture content within RPG creation articles, whereas discussions on RPG creation were notably less prevalent in articles concerning narrative architecture design. Lastly, in the fourth phase, we synthesize and discuss the literature on interdisciplinary applications to address our research inquiries.

4. Creative methods for teaching narrative architectural design and creating role-playing game

4.1. THE BASIC STEPS, PROBLEMS AND SOLUTIONS OF NARRATIVE ARCHITECTURAL DESIGN TEACHING

Narrative architecture constitutes a form of architecture where spatial development revolves around narrative progression. Bleeckere and Gerards (2017) assert that architects employ storytelling to convey design concepts within narrative architecture, shaping architectural scenes and spatial layouts based on these narratives. In architectural design education, as summarized by Coates (2012), narrative architectural design encompasses 8 components: Narrative Concept, Spatial Design, Interactive Design, Contextual Integration, and Iteration and Feedback. Within the Narrative Concept phase, architects engage in three stages: site analysis, case study, and narrative content development, facilitating the gradual clarification of direction and vision, the acquisition of insights and inspiration, and the formation of final narrative content (Ryan, Foote and Azaryahu, 2016). According to Psarra (2009), the aim of the Narrative Concept stage is to yield narrative content anchored in the context and aligned with envisioned objectives, serving as a reference and foundation for subsequent architectural design.

In the Spatial Design phase, architects translate narrative content into spatial qualities and architectural forms. Spatial layout, symbols and metaphors, architectural technology, and sensory design are primary components, respectively addressing spatial circulation patterns (Smith, 2001), conveying specific meanings (Eilouti, 2018), enhancing user experience (Bleeckere and Gerards, 2017), and utilizing sensory stimuli to connect users with buildings (Goldblatt, 2020). Concerning the Interactive Design stage, Goldblatt (2020) emphasizes that the objective is to ensure that architectural space serves as a platform for users to interact, explore, and collaboratively craft their narrative experiences through user engagement in design, aiming to deepen their connection to spatial concepts and overarching narratives.

In the preceding two stages, the architect establishes their foundational design logic for the project and completes the initial architectural design. Subsequently, within the Contextual Integration phase, architects evaluate the harmony between the narrative design and the site's context, entailing a critical assessment of their prior design choices (Childs, 2008). However, the validation and critique aspects inherent to the Contextual Integration phase can impose significant pressure on architects, particularly those lacking experience. According to Soliman (2017), the design logic crafted by architects during the Spatial Design and Interactive Design stages might encounter challenges during the contextual integration phase, leading to confusion and impacting overall design control. For architecture students in the learning stage and lacking experience, Torres (2015) highlights that the aforementioned issues can hinder students from establishing the connection between narrative concepts and architectural design, resulting in a disconnect between architectural design endeavors and narrative content.

To address these challenges, certain architects elect to consider all three phases within the design process. Psarra (2009) introduced a design approach that amalgamates and synchronizes the Spatial Design, Interactive Design, and Contextual Integration stages, positing that this could assist architects in averting major discrepancies between phases (Figure 2.). Moreover, Psarra (2009) noted that this method empowers architects to promptly identify contradictions and architectural flaws, thereby reducing the psychological stress and self-doubt associated with troubleshooting and error correction.

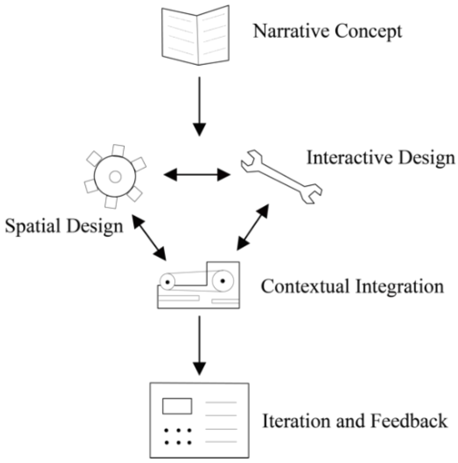

Figure 2. Basic Steps in Narrative Architecture Design (drawn by first author)

However, Nazidizaji (2015) and his research team raised concerns, contending that the logical thinking demanded by this approach erects fresh hurdles for architects and architecture students lacking design experience. They underscore that concurrently managing numerous elements like architectural components, spatial layout, sensory experiences, interaction methods, and narrative coherence necessitates advanced logical thinking skills, work experience, memory, and imagination. Hettithanthri and Hansen (2022) also expressed apprehension that students with limited architectural exposure may grapple with cognitive inconsistencies or paradoxes while adopting this approach, finding it arduous to establish a unified working logic amid the vast reservoir of existing knowledge. Insufficient working logic can impede the establishment of a nexus between narrative concepts and architectural design, ultimately yielding architectural design endeavors that remain detached from narrative content (Torres *et al.*, 2015).

4.2. THE BASIC STEPS, PROBLEMS AND SOLUTIONS OF RPG CREATION

As per Skolnick (2014), the objective of RPG creation is to establish a compelling sense of immersion to articulate narrative content by materializing it, ultimately meeting players' expectations. Research by Brown and Cairns (2004) indicated that early RPG creation relied on planners' artistic prowess. They highlighted that inadequate personnel experience and proficiency could lead RPGs to confront the issue of lacking internal coherence between the background story and scene content. To address these challenges, Bethke (2003) posited that the RPG creation method involves first establishing the game's background worldview and subsequently refining the narrative while shaping scenes. Media scholar Petrillo (2009) delineated this process, encompassing eight components: Conceptualization, Pre-production, Art and Asset Creation, Programming and game implementation, Level design and content creation, Playtesting and iteration, Certification and release, and post-release support.

Based on Reardon and Wright's theory (2021), contemporary RPG creation embodies a form of "experience design" that seeks to engage various senses of the human body, comprehensively influencing players' emotions through diverse sensory stimuli to enhance the communication of narrative content. Within the Art and Asset Creation stage, visual assets establish a visually cohesive and immersive environment through landscapes, structures, props, and other in-game elements, contributing to the overall RPG atmosphere and sense of place (Cairns, Cox and Nordin, 2014). During the Level Design and Content Creation phase, environmental storytelling employs visual and interactive components to craft environments fostering immersion and exploration, facilitating narrative transmission and enriching experiences (Ramadan and Widyani, 2013). By utilizing sensory stimulation to steer players toward specific emotions, RPGs effectively immerse players in the narrative content, thus achieving a fusion of narrative and environmental elements. Bormann and Greitemeyer's study (2015) on In-Game Storytelling underscores that adept RPG works elicit distinct emotional impacts with each story scene, significantly aiding narrative presentation.

Today's RPG creation process can be viewed as a design approach involving planning, division, and integration (Figure 3.). The planning component encompasses the Conceptualization and Pre-production stages. Ramadan and Widyani (2013) depict the Conceptualization stage as the time when designers amalgamate market needs and team concepts to formulate a comprehensive background framework for the game. Aleem, Capretz, and Ahmed (2016a) posit that in the Pre-production stage, designers are tasked with gathering reference materials concerning art style, music, and narrative elements, employed to explore the requisite game elements for this genre.

The division segment encompasses the Art and Asset Creation and Programming and game implementation phases. Cairns, Cox, and Nordin (2014) characterize the task of designers in the Art and Asset Creation stage as breaking down the game world into components and generating art assets based on background settings. Bethke (2003) delineates the Programming and game implementation stage as involving developers writing code to transform art assets into game components usable within the game engine and constructing fundamental game operational mechanisms.

Lastly, the integration phase occurs within the Level design and content creation stage. In line with Skolnick's assertion (2014), the level designer utilizes previously generated game scene materials to craft the level scenes in accordance with each level's narrative content, thereby achieving the construction of the game scenes.

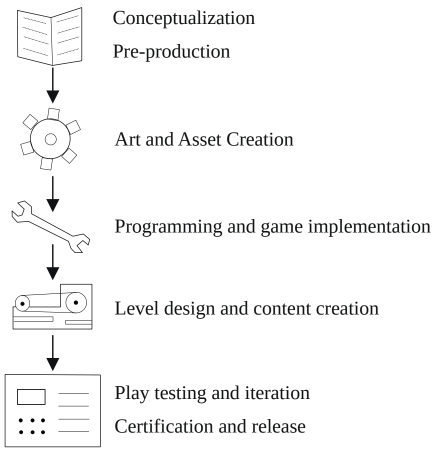

Figure 3. Basic steps of RPG creation (drawn by first author)

Bethke (2003) contends that the novel RPG authoring method empowers game designers to disintegrate design tasks into sequential phases. In this process, designers outline requisite game components during the initial stage, continually produce assets during subsequent phases, and ultimately employ these prepared assets for storytelling and scene design in the final phase (Aleem, Capretz and Ahmed, 2016b). Reardon and Wright (2021) affirm that this approach enables designers to articulate their requisites and progressively fortify the game's background settings, ensuring a robust correlation between physical content and the narrative storyline.

4.3. INTERDISCIPLINARY APPLICATION OF NARRATIVE ARCHITECTURAL DESIGN TEACHING AND RPG CREATION

The objective of narrative architecture is to communicate the architect's design philosophy by amalgamating architectural and narrative elements (Bleeckere and Gerards, 2017). RPG creation's purpose is to establish a compelling sense of immersion for expressing narrative content by materializing it (Skolnick, 2014). Both pursuits strive to engender highly immersive scenes that align with narrative content. This has led some experts and scholars to contemplate the potential for reciprocal referencing between the two disciplines and prompted the exploration of interdisciplinary applications between narrative architecture and RPG in the creative process.

The initiative of interdisciplinary application within RPG creation began with the work of RPG creators. In the paper "Narrative Environments," Pearce (2007) delved into the evolution of video games and observed that as 3D technology and real-time 3D emerged, video games increasingly embraced themes and design principles akin to those found in theme parks. Drawing from Disneyland's design concepts, the author examined the visual aspects of various video games, including the "Monkey Island" series (1990-2000), uncovering the widespread integration of urban design theory to craft coherent narrative spaces. Bridges and Charitos (1997) explored the potential amalgamation of architectural design and film theory knowledge within virtual environment (VE) design in their paper "On architectural design in virtual environments". They posited that these domains offer valuable frameworks for ideation and VE design guidance, underscoring the importance of embedding theoretical and practical architectural insights into the VE creation process. Jenkins (2004) conducted an in-depth exploration of the interplay between narrative and interactivity in games, along with the potential influence of architectural design theory on game development through the paper "Game design as narrative architecture". The author accentuated the role of storytelling in games, pivotal for fostering player immersion and emotional engagement. Confronting these challenges, Jenkins advocated for an approach to game design that draws from architectural design techniques. This strategy aims to incorporate interior decoration and building block amalgamation concepts from architectural design to construct rational and visually impactful game environments, ultimately yielding a more organic and captivating gaming experience.

Nevertheless, in the realm of teaching narrative architectural design, the incorporation of references from RPG creation has been notably diminished. In their paper "Building a World-View: Visual Communication in Classic Maya Architecture," William and Barbara (1996) referenced background design concepts from RPGs in their study on Mayan architecture, drawing parallels between the broader Mayan worldview and the stylistic and visual language of Mayan architecture. By integrating the background design principles from RPG creation, they posited that Mayan architecture initially established a cultural worldview as the foundational framework for shaping architectural forms. Their research underscores that leveraging a predetermined background worldview can foster greater coherence and seamlessness in architectural scene design. Lim (2013), a UCL scholar, transposed elements from the "Conceptualization" phase of RPG creation into his urban design study of London. Article "London Short Stories: Drawing Narratives" lauds the role of narrative and symbolism in architecture and outlines Lim's project, London Short Stories, which employs "real and imagined locations as springboards for the imagination." Through crafting settings and generating visual content rooted in these settings, along with crafting a narrative storyline, the author generates captivating narrative material. The final architectural output was lauded as "aesthetically dazzling, captivating, and visually pleasing."

5. Summary and Discussion of Screened Papers

Both narrative architectural design teaching and RPG creation share the objective of crafting deeply immersive scenes that align with narrative content. Some experts and scholars have initiated cross-disciplinary insights from both domains. Taking Jenkins (2004) as an illustrative example, researchers in game creation have enhanced the visual effects of interior scenes and architectural components in RPGs through extensive utilization of architectural research findings, particularly those concerning architectural interior decoration and building block combinations. However, despite the potential for interdisciplinary integration of RPG creation into narrative architectural design instruction, such applications remain limited. In pioneering initiatives within certain educational institutions, a handful of scholars have also explored incorporating elements from the "Conceptualization" phase of RPG creation into architectural design and urban planning research (Lim, 2013).

Figure 4. Concept prototype: the habitable spaces within extend and unfold each morning to provide a stage set for grooming, relaxation and dining. (Lim, 2013, p. 103)

However, the reference significance of how RPGs, which excel in impacting player emotions through apt scene design to enhance narrative delivery, remains unexplored for narrative architecture.

When reviewing the creative methods of both disciplines, it becomes evident that in the teaching of narrative architectural design, while certain solutions have been proposed, the current design approaches still fail to address the issue of detachment between architectural design endeavors and narrative content arising from students' limited design experience (Torres et al., 2015). In contrast, within the realm of RPG design, an observable trend is the development of methods aimed at rectifying the lack of coherence between background stories and scene content due to the inexperience of production personnel (Brown and Cairns, 2004). The extant RPG creation methodologies employ an "experience design" approach, leveraging scene design to influence players' emotions and immerse them in the narrative content, thereby fostering the integration of narrative and environmental elements (Reardon and Wright, 2021). Within successful RPG titles, individual story scenes wield specific emotional impacts to bolster the narrative's presentation (Bormann and Greitemeyer, 2015). Analyzing the "interplay between scene design and emotional expression" in accomplished RPGs can potentially illuminate the correlation between architectural settings and emotional resonance, facilitating the establishment of a connection between "narrative content - required emotion - architectural scene." This understanding is highly advantageous for architecture students in their pursuit of narrative architectural design proficiency.

6. Conclusion

The objective of narrative architecture is to convey the architect's design philosophy by amalgamating architectural and narrative elements (Bleeckere and Gerards, 2017). However, for architecture students, grasping the 8 fundamental steps of narrative architectural design during their architectural education proves challenging. This often results in their struggle to establish the correlation between their narrative concepts and architectural design, ultimately causing a disjunction between their architectural creations and narrative content (Torres et al., 2015). To address this predicament, the proposal of conducting coherence checks within the Contextual Integration stage, concurrently with the initial two design stages, emerged (Psarra, 2009). Yet, the prerequisite of possessing logical thinking skills in executing this approach presents fresh hurdles for students (Nazidizaji et al., 2015). Ultimately, this still leads to a detachment between students' architectural designs and narrative content (Torres et al., 2015).

The aim of RPG creation is to establish a compelling sense of immersion to convey narrative content by manifesting it (Skolnick, 2014). Many early RPGs encountered the issue of a lacking inherent connection between background stories and scene content (Brown and Cairns, 2004). The introduction of the RPG creation method, which involves crafting the game's background world view before refining the story and constructing scenes in alignment with the overarching world view, addresses this concern (Bethke, 2003). This approach guarantees a robust correlation between physical and narrative content, particularly benefiting inexperienced designers (Reardon and Wright, 2021). Presently, the RPG creation process emphasizes an all-encompassing influence on players' emotions through diverse sensory stimuli in scene design, facilitating their immersion into the narrative content and achieving enhanced expression of the narrative (Reardon and Wright, 2021).

Recognizing the partial alignment of their creative objectives, certain experts and scholars have commenced cross-disciplinary investigations between narrative architecture and RPG creation. Game researchers like Jenkins (2004) optimize visual experiences within RPG creation by drawing from architectural theory. Some architectural scholars attempt to apply narrative storytelling techniques from RPGs to architectural research (Lim, 2013), focusing on the use of effective scene design to impact player emotions and enhance narrative delivery. However, scant attention has been directed towards exploring the instructional value of this aspect for narrative architectural education. Investigating the "relationship between scene design and emotional expression" in exemplary RPGs could help establish the connection between "narrative content-emotion-architectural scene," serving as a valuable resource for architecture students learning about narrative architectural design.

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4.B.

BUILDING INFORMATICS AND PARAMETRICS - III

DEEP ARCHITECTURAL FLOOR PLAN GENERATION: AN APPROACH FOR OPEN-PLANNED RESIDENTIAL SPACES

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Abstract. This research investigates the collaborative potential of artificial intelligence and deep learning in architectural design, focusing on comprehending and synthesizing the complex relationships within architectural floor plans. The primary question addressed is whether deep learning algorithms can effectively generate residential floor plans characterized by open-planned architectural spaces. To address this, the study introduces a novel model employing generative adversarial networks (GANs) to create open-planned layouts within residential floor plans. Open-planned spaces refers to a design approach in which interior spaces within a structure are intentionally devoid of traditional partitioning elements such as walls and doors. The layout typically features interconnected and visually continuous spaces that flow seamlessly from one area to another. The research contributes by addressing a gap in the literature through the exploration of functional space differentiations within residences characterized by open plan arrangement without walls as a separating element. Furthermore, the study extends this investigation by applying the proposed methodology to angular and circular plans as well as orthogonal plan sets. In the generative model created with GAN, the space functions are defined and labelled with the RGB color codes assigned to them. For the RGB label representation of the open-plan layout, gradient coloring prepared. By using this method, it was investigated whether the generation of the plans was realized with an open-plan structure by examining the gradient generation results. In the generative model, the footprint of the plan is given as an input for the algorithm to produce by adhering to an outer boundary. Accordingly, it is aimed to learn how the network can be arranged within the given boundaries. The Pix2pix method was used for this generative model, which is defined as the problem of obtaining images from images. The model results advance the AI-driven understanding of architectural design by providing architects with an innovative tool to explore open-plan spatial solutions.

Keywords: *floor plan generation, deep learning, generative adversarial networks.*

ملخص. تبحث هذه الورقية البحثية في الإمكانات التعاونية للذكاء الاصطناعي والتعلم العميق في التصميم المعماري، مع التركيز على فهم وتجميع العلاقات المعقدة ضمن مخططات الطوابق المعمارية. السؤال الأساسي الذي يتم تناوله هو ما إذا كانت خوارزميات التعلم العميق يمكنها بشكل فعال إنشاء مخططات سكنية تتميز بمساحات معمارية ذات مخطط مفتوح. ولمعالجة ذلك، تقدم الدراسة نموذجًا جديدًا يستخدم شبكات الخصومة التوليدية (GANs) لإنشاء تخطيطات مفتوحة ضمن مخططات الطوابق السكنية. تشير المساحات ذات المخطط المفتوح إلى أسلوب التصميم الذي تكون فيه المساحات الداخلية داخل المبنى خالية عمداً من عناصر التقسيم التقليدية مثل الجدران والأبواب. يتميز التخطيط عادةً بمساحات مترابطة ومستمرة بصريًا تتدفق بسلاسة من منطقة إلى أخرى. يساهم البحث من خلال معالجة فجوة في الأدبيات من خلال استكشاف الفروق المكانية الوظيفية داخل المساكن التي تتميز بالترتيب المفتوح بدون جدران كعنصر فاصل. علاوة على ذلك، توسع الدراسة هذا البحث من خلال تطبيق المنهجية المقترحة على المخططات الزاوية والدائرية بالإضافة إلى مجموعات المخططات المتعامدة. في النموذج التوليدي الذي تم إنشاؤه باستخدام GAN، يتم تعريف وظائف المساحة وتسميتها برموز ألوان RGB المخصصة لها. لتمثيل تسمية RGB للتخطيط المفتوح، تم إعداد تلوين متدرج. باستخدام هذه الطريقة، تم التحقق مما إذا كان إنشاء الخطط قد تم تحقيقه بهيكل مفتوح من خلال فحص نتائج توليد التدرج. في النموذج التوليدي، يتم تقديم بصمة الخطة كمدخل للخوارزمية لإنتاجها من خلال الالتزام بالحدود الخارجية. وبناء على ذلك، يهدف إلى معرفة كيفية ترتيب الشبكة ضمن الحدود المعطاة. تم استخدام طريقة Pix2pix لهذا النموذج التوليدي الذي يعرف بأنه مشكلة الحصول على الصور من الصور. تعمل نتائج النموذج على تعزيز الفهم القائم على الذكاء الاصطناعي للتصميم المعماري من خلال تزويد المهندسين المعماريين بأداة مبتكرة لاستكشاف الحلول المكانية ذات المخطط المفتوح.

الكلمات المفتاحية: *توليد المساقط الأفقية، التعلم العميق، شبكات الخصومة التوليدية.*

1. Introduction

A floor plan can be defined as a bi-dimensional representation of the spatial configurations and dimensions of spaces. Different spatial configurations define different spatial boundaries, leading to a unique spatial experience. The complex relationships represented in architectural plans are mainly based on dynamic interactions of perceiving and traversing spatial spaces. The accessibility provided by spatial functions are supported by topological relationships that govern the flow and connection of architectural spaces. In addition, the visual interaction between spaces is realized through openings such as windows and galleries, creating an interaction of vision and visibility. It is noteworthy, however, that factors such as visual relationships that determine the experiential quality of architectural spaces are often not included in architectural plan-generating processes.

Models used in architectural plan generation are mostly based on defined topological relations, constraints such as not overlapping spaces, leaving undefined areas, and/or objectives such as minimizing the circulation area. Topological relations represent architectural units that should be close to each other depending on the building organization. This relationship is based only on the physical proximity-distance relationship between spaces. Lobos and Donath (2010) divide architectural plan generation criteria into measurable rational criteria and unmeasurable design criteria. While rational criteria can be counted as sun, landscape, accessibility, proximity of related functions, minimizing circulation areas, unmeasurable design criteria are defined as geometric composition, form formed in third dimension, aesthetics of form / golden ratio etc. Existing models are inadequate of specifying whether the spaces are separated by a direct opening, a door, a solid wall surface, or a surface that is transparent like glass and allows to see/be seen. While a transparent wall surface does not prevent the act of seeing, it limits the act of going. A solid wall surface creates both a visual and a physical boundary. For this reason, the definition of topological spatial relationship based only on the proximity-distance relationship is insufficient to represent the architectural space. In architecture, spatial divisions can be defined as separate rooms separated by physical walls. However, one of the basic principles of architecture is that the use of space within a building should be flexible or flexible (Jabi et al., 2018). For this reason, the topological relations of the open plan layout that allows multiple uses is important.

The aim of the research is to investigate whether deep learning algorithms can make inferences about the visual relationship of spaces from the training sets, and the visual and physical relationship required by the architectural space function (while spaces such as bedrooms and bathrooms have less visual and physical relationships due to the privacy situation, common use spaces such as living rooms have higher) or not.

As Stiny (2006) mentioned “Spatial relations for a given vocabulary sometimes allow its shapes to interpenetrate in designs. Interpenetration like spatial ambiguity can be a valuable technique in design.” Spatial ambiguity is a quality of space that an architect can deliberately incorporate into the building design while providing a subjective experience from the user's point of view. The concept of flexibility, a product of the Modern Movement in Architecture, gained importance after the 1950s, adding the elements of "time" and "unknown" to the design and brought a new breath to functional architecture. According to Collins (1968), “flexibility is a kind of functionalism” and he defines flexibility as a closed circuit that is specified by the architect, specialized for not one but more than one configuration. Spatial ambiguity occurs in open, flexible plan designs where the spatial configuration does not reveal clear and precise functional distinctions. In this study, it is suggested to create floor plan images with gradient coloring for the flexible arrangements in the plan and the visual relationships resulting from it.

The image consists of the combination of more than one pixel. The whole of the techniques whose input is image and output is information in different modalities is called "computer vision". The output of computer vision techniques is semantic information related to the input image or derived from the input images. For the recognition and the generation of the floor plan visuals, it is important to learn the semantic information contained. Floor plan recognition is different from other separation methods. Because the elements that make up the plan are not only found singularly, but the relationship also they express with each other and the spaces they represent are important. Computerization and, in particular, computer vision presents a new opportunity for expressing the general cognitive mechanisms and the domain knowledge contained in these representations. It is a powerful method used on visual data and has good potential for recognizing and generating architectural drawings. Therefore, architectural housing plan design as a complex and ill-defined problem is investigated with deep learning methods, which is a sub-branch of artificial intelligence. The paper presents a novel model that aims to generate open-planned architectural spaces represented in residential floor plans with generative adversarial networks (GANs) which is one of the deep generative networks.

2. Related Works

The methods used in the architectural plan generation can be listed as shape grammars, genetic algorithms (GA), general probabilistic methods, growth models and deep generative models. In deep learning, neural networks are not structured according to rules or previous algorithms, they learn patterns/patterns with training sets. This contrasts with previous generative design approaches. For example, in shape grammars, the initial form and the rules to be applied repeatedly are determined by the designer. In deep learning, on the other hand, the rules for combining shapes and forms are not predetermined, the algorithm discovers them from the training data.

In the plan generation and optimization studies made with genetic algorithm, the process of finding the most suitable ones for the fitness function or more than one conflicting function from the solution set in a research space is followed. As an early example of architectural space arrangement, Rodrigues, Gaspar, & Gomes (2013) created an optimization model by considering contiguity, space overlap, span overlap and orientation, floor dimensions and overhang. They applied this framework to the housing plan generation problem to validate the proposed method. In another example of a residential setting, they used GA to maximize symmetry, structural safety, stair connectivity, and the amount of daylight exposure of the facades (Song et al., 2016). In GAs, the fitness function is calculated over the defined design variables. Therefore, unlike deep learning, these functions and variables are determined by the designer.

General probabilistic approaches have explored the application of Bayesian networks (Merrell et al., 2010) and Markov chains (Swahn, 2018) to learn from sample images in the synthesis of the architectural plan.

In cellular automata, which is one of the growth models, cells arranged on regular Cartesian grids in two or three dimensions are loaded with predefined states with neighborhood relations that differ depending on the rules (Dincer et al., 2014).

Deep neural networks mimic the inner workings of the human brain and consist of (1) an input layer, (2) hidden layers (which process data), and (3) an output layer that produces results. It can be reconfigured, and the weights of neurons can be manipulated iteratively to improve its performance. In this training process, DNN (Deep Neural Networks) learns to get the right output in the process.

As et al. (2018) proposed a generation model with deep artificial neural networks, using sets of architectural plans represented as “graphs” along with the livability and adaptability criteria. The algorithm proposes a new architectural plan with orthogonal designs by combining the subgraphs. However, the limited sample dataset and subjective evaluation processes restrict its general applicability.

Alternative approaches have been explored, including recognizing architectural plans from color-labeled images (Huang and Zheng, 2018). The algorithm demonstrates a strong capability in identifying spaces with well-defined boundaries and distinct features like bedrooms, kitchens, and toilets. However, it encounters challenges when distinguishing spaces where boundaries converge, as seen living rooms and corridors. The algorithm does not propose a new plan with different topological relations but aims to reach the architectural plan representation output from the image represented by color labels. Notably, it did not perform well with non-orthogonal plans due to the dataset's dominance of orthogonal plans.

Wu et al. (2019) introduced DeepLayout, focusing on residential architectural plans. It relies on predefined room connections and layouts, with user interaction options, but lacks circulation area definition. DeepLayout had challenges in placing sufficient space and even privacy issues such as the transition from the bathroom to the balcony emerged. Additionally, Hu et al. presented Graph2Plan, a learning-based approach that adapts similar layouts to given input boundaries. Both DeepLayout and Graph2Plan require predefined rules for door and window placement, whereas our approach learns these rules from data.

Nauata et al. (2020) propose HouseGAN, a graph-constrained generative adversarial network, to generate floor plans based on room types and spatial relationships. It encountered issues with room sizes, shapes, placement, and inaccessible spaces. The model does not consider space sizes, only assigning rectangular forms to spaces without addressing doors and windows. FloorGAN (Abhinav et al., 2023) designed to create floor plans while adhering to user-defined constraints via graphs. This approach incorporates user input, including room types and spatial relationships, to generate layouts that comply with these specifications.

All these mentioned models deal with the issue of generating floor plan either as a topological relationship, and (or) simply a coloring problem according to a function definition only. However, a floor plan is not just a visual combination of architectural elements such as walls, doors, windows, furniture. It is a visual representation of how they relate to each other and how they are arranged to create different types of spaces and experiences. Therefore, the presented research does not limit itself to rectangular plans only; expands its floor plan generation reach to angled and curved designs. The importance of visual relationships as well as topological relationships in the process of creating architectural plans is also emphasized by working on open-planned architectural plans. Furthermore, the primary objective of this research is to unleash the algorithm's creative capabilities, allowing it to generate original designs without imposing strict constraints dictated by a mere graph.

3. Methodology

In the proposed generative model, it is aimed to make the application in angular and circular plans as well as orthogonal plan sets, and to consider the functional area differences in the residential plans with an open/flexible plan arrangement without walls within the scope of the model. In line with these goals, gradient coloring is suggested for RGB label representation of flexible layout. Recoloring studies on R3D dataset were carried out according to the proposed gradient coloring method. In this way, the gradient generation outputs are explored as a result of the generative model. Generative adversarial networks are selected for this model. GANs, learn statistically significant phenomena from the data presented to them without the need for labels and produce visually realistic images. GANs are generative models that learn to map an output image from a random noise vector (Goodfellow et al., 2014). In this section, the proposed gradient coloring method and the network architecture used for the preparation of the data set are explained in this section.

3.1. PREPARATION OF DATASET AND LABELING PRINCIPLES

The data set used in this study is R3D data set which is prepared by Zeng et al. (Zeng et al., 2019) with R2V data set. R2V mostly consists of rectangular shaped plans with uniform wall thickness images from Raster-to-Vector (Liu et al., 2017). A total of 182 plan images were used, 131 of which had an open plan layout. For R3D, rounded-shaped floor plans were added to the dataset by Zeng alongside the original images in Rent-3D (Liu et al., 2015). 112 of the 194 plan images have an open plan layout. Compared to R2V, R3D has non-orthogonal plan sets with nonuniform wall thickness (Zeng et al., 2019) (Fig.1). While 168 of the images selected from the R2V plan set are orthogonal plans, this number is only 32 in R3D. Both data sets are open-source sets that can be accessed from given references.

Figure 1. Comparison between the R2V (left) and R3D (right) data sets (Zeng et al., 2019).

In these datasets, the same label is used for some open-planned zones, such as the living room and the dining room, that generally do not have separating walls and are mostly adjacent to each other. In this study, we used different labels to separate the connected room zones, even though they are located next to each other without walls separating them (Fig. 2). Due to the spatial ambiguity of open-plan spaces, it is not clear exactly where space functions begin and end. Gradient coloring representation is suggested for the representation of such spaces with RGB color labels. A gradient is a path from one color to another in a color space. Just as a line segment can go from (x_1, y_1, z_1) to (x_2, y_2, z_2) in 3-dimensional space, so a color be reached from rgb(r_1, g_1, b_1) to rgb(r_2, g_2, b_2) in RGB space. The gradient transition does not always have to be linear. Gradient color transitions can be created in a free form determined by points as well as linear, radial, or reflected. Each sub-gradient color (c(n)) is calculated for each pixel transition on the gradient path.

Where the starting color (c_1) of the gradient is defined as rgb (r_1, g_1, b_1), the end color (c_2) of the gradient is defined as rgb (r_2, g_2, b_2) and p is the total number of pixels of the image.

When the gradient process on an image proceeds incrementally in equal intervals, the first step in computing the sub-gradient color is taking the difference between the R, G, and B channels of the colors. Then this difference is divided by the total number of pixels for which the gradient will be created. Each of these values are added to the R, G, and B channels for each subsequent transition in the gradient as shown in Eq.1.

$$c(n) = rgb(r_1 + \left(\frac{r_2-r_1}{p}\right) * n, g_1 + \left(\frac{g_2-g_1}{p}\right) * n, b_1 + \left(\frac{b_2-b_1}{p}\right) * n) \tag{1}$$

However, in a space with an open plan arrangement, the spatial distribution of functions is not always equal. For example, in the distribution of the living room and the dining room in a space, the living area usually occupies a percentage of more space.

For this, the distribution scale of the spatial function change is determined and the pixel values in the distribution range where this change occurs are in the middle transition color (c_{avg}) of these two colors. It is defined as rgb (r_{avg}, g_{avg}, b_{avg}) and calculated by taking the arithmetic average of each R, G, and B channels of the starting and end color (Eq.2).

$$\begin{aligned} c_1 &= rgb(r_1, g_1, b_1) \\ c_2 &= rgb(r_2, g_2, b_2) \\ c_{avg} &= rgb\left(r_{avg}, g_{avg}, b_{avg}\right) = rgb(\frac{r_1+r_2}{2}, \frac{g_1+g_2}{2}, \frac{b_1+b_2}{2}) \end{aligned} \tag{2}$$

The pixel location of each subsequent transition is important for the definition of the transition state between spaces. Calculation of subsequent colors interval positions differ depending on whether the range field (x) is before (closeness to the starting color) or after (closeness to the end color). Number of pixels on either side of the range field is calculated by multiplying the inter-functional distribution scale value of an open space (s) with the total number of the pixels. Accordingly, the color change between pixels is calculated as denoted in Eq.3.

$$\begin{aligned} & if\ s.p \leq x\ \ then \\ & c(n) = rgb\left(r_1 + \frac{r_{avg}-r_1}{s.p}, g_1 + \frac{g_{avg}-g_1}{s.p}, b_1 + \frac{b_{avg}-b_1}{s.p}\right) \\ & else\ c(n) = rgb\left(r_{avg} + \frac{r_2-r_{avg}}{(1-s).p}, g_{avg} + \frac{g_2-g_{avg}}{(1-s).p}, b_{avg} + \frac{b_2-b_{avg}}{(1-s).p}\right) \end{aligned} \tag{3}$$

The suggested gradient coloring method was applied to these plans by using Adobe Photoshop and Illustrator to manually recolor spatial differences in open-plan areas. Table 1 shows the detailed colors and RGB codes used.

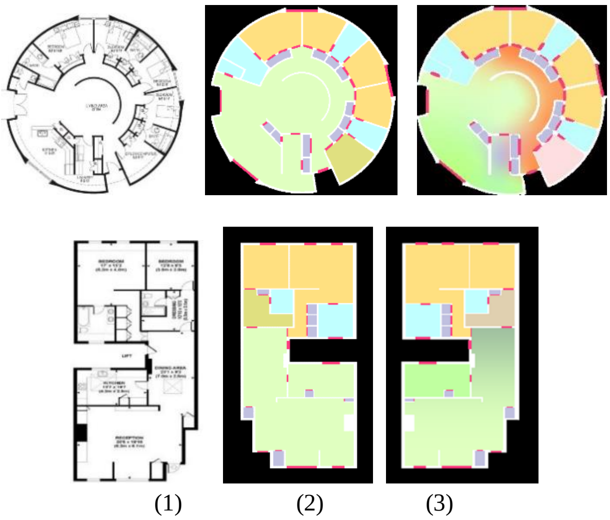
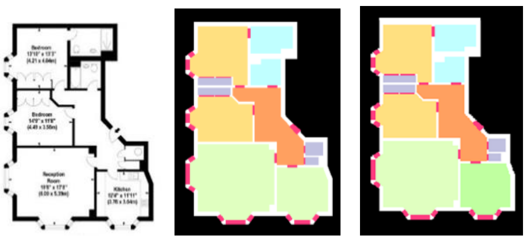


Figure 2. (1) Floor plan (2) R3D data set coloring (3) Proposed gradient recoloring in open-planned spaces ID.3 (top) – ID. 45737995 (bottom)

TABLE 1. RGB code and representations of each usage label.

Space usages	RGB Code and RGB color representation
Living room (LivR)	224, 255, 192
Kitchen (Ktch)	192, 255, 160
Dining room (DinR)	160, 192, 160
Bath / WC (BthR)	192, 255, 255
Bedroom (BedR)	255, 224, 128
Dressing room	224, 208, 176
Study room (StdR)	255, 224, 224
Storage	192, 192, 224
Corridor / hallways (Hall)	255, 160, 96
Courtyard	192, 192, 192
Fireplace	224, 224, 224
Windows/doors	255, 60, 128
Wall	255, 255, 255

In addition, even if two separate spaces are separated by a wall, if they are defined by the same color, these spaces are also separated. For example, with the ID 45665893 plan, both the living room and the kitchen are represented in light green. The kitchen space has been recolored with dark green (Fig. 3).



(1) (2) (3)

Figure 3. (1) Floor plan (2) R3D data set coloring (3) Proposed recoloring in different spaces separated by a wall ID.45665893

The walls are defined with white color (255, 255, 255) and the remaining area with black (0, 0, 0) so that the computer does not spend too much calculation time in the surrounding visual areas where there is no plan image. In the generative model, it is thought that the footprint of the plan in the field is given as input in order that the algorithm produces by adhering to an outer boundary. Accordingly, it is aimed that the deep network learns how to arrange a plan within the given boundaries (Fig. 4). The prepared data set was prepared with input and output images of 512x256 pixels. Then, the image is divided into two, half of which is 256x256 pixels as input and the other half of 256x256 pixels is processed as output label.

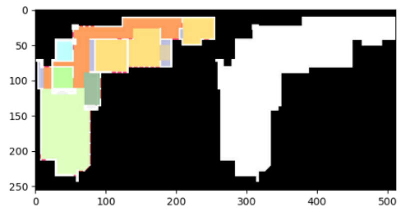


Figure 4. Input and output image prepared for the generative model ID.5

3.2. NETWORK STRUCTURE

The Pix2pix (Isola et al., 2017) network was used for the generative model, which is defined as the problem of obtaining images from images. Pix2pix is one of the conditional adversarial networks used in image-to-image conversion. These networks learn to map from input image to output image. This approach has been shown to be effective in synthesizing images from tag maps, reconstructing objects from edge maps, and coloring images. It consists of two main artificial neural networks: Generator and Discriminator.

The discriminative network is trained to recognize the images in the training set. In the generative network, a footprint image of a floor plan was used as input and it is aimed to generate new visuals as closely as possible to the visuals in the training set. The discriminator tries to distinguish whether the images from the generator are real or fake (Fig.5). As the generative network evolves, it learns to generate more lifelike images, while the discriminating network can differentiate between the actual image and the generated one. The development of the generative network occurs as a result of feedback according to the error values obtained with the loss function of the discriminator (Goodfellow et al., 2014). For this type of competitive training, the goal is to achieve a Nash equilibrium (Heusel et al., 2017) where the generated images are indistinguishable from real images.

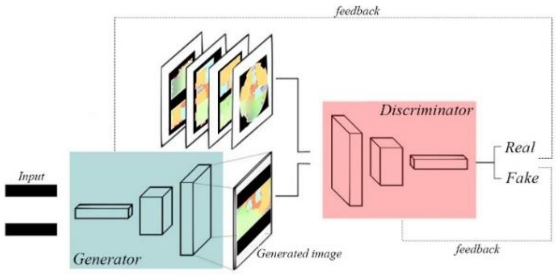


Figure 5. Diagram illustrating the process of Pix2Pix network.

Combination of some deep learning techniques is described to train GANs. These techniques include: (i) fully convolutional network and (ii) Batch Normalization (BN). In the convolutional network, filtering operations are used to increase and decrease the spatial dimensions of the image. BN normalizes feature vectors to have zero mean and unit variance across all layers. This helps stabilize learning and cope with poor weight initiation problems (Radford et al., 2015). The steps performed in this study are represented in the network architecture diagram with the number of channels (Fig. 6). The down-sampling and up-sampling in generator networks consist of 4x4 convolution filters with stride of 2. It is followed by a BN and rectified linear unit (ReLU). In activation function of ReLU, if a value is negative, it passes 0, if it is positive it passes as it is (Zhao et al., 2020). It behaves like human neurons; they do not respond to signals below a certain level. In spite of this, the discriminator down-sampling step uses the Leaky ReLU function. The difference of Leaky ReLU from ReLU is that instead of resetting negative values, it returns a very small value. With this situation, it is aimed to prevent dead neurons.

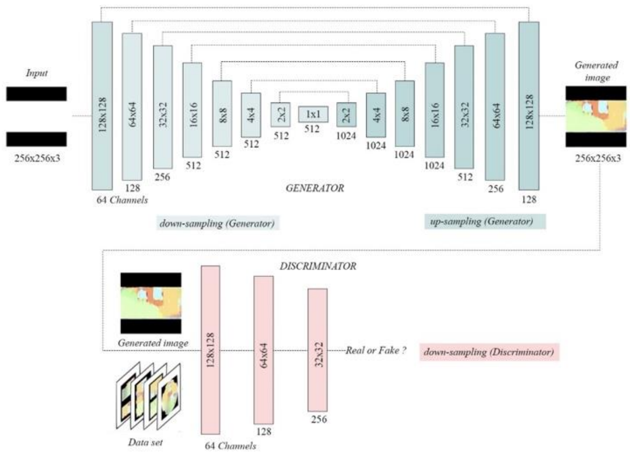


Figure 6. Diagram illustrating the network architecture of Pix2Pix.

4. Results

Three distinct input image categories were selected to facilitate a comprehensive comparative analysis of generative outcomes obtaining to the model trained using the R3D dataset. The primary input form includes an assessment of generative outputs within the context of orthogonal scenario, as shown in Figure 7. On the other hand, the input of the second generative model were chosen to generate angular configurations as in Figure 9. Lastly, a circular input image was selected to evaluate the efficacy of floor plan generation in accommodating curvilinear forms, as presented in Figure 11. All training and generating operations are performed using NVIDIA GeForce RTX 2070 GPU. The model prints the image on the screen after 10 epochs and stops the progress of the model after 190 epochs. It takes between 200-300 seconds to complete each epoch steps. It takes approximately 10 hours for the model to complete the process.

From the 30th epoch, the recessed orthogonal plan, started to be formed around the corridor placed in the lower juncture corner. The upper horizontal rectangular section has been designated as a common living area consisting of a living room and an open kitchen since the early epochs. The bathroom is adjacent to the common living area and the bedroom, connected to the corridor (Fig. 7).

L1 loss (defined as the least absolute deviations) is calculated between the images generated by the model and the actual images. This loss function should be as small as possible to allow the generator network to fool the discriminator. At the end of the training, the generator loss was 0.74, and the discriminator loss was 0.62. Increasing this distance means that the generated images move away from the images in the training set, that is, the generating network is not trained.

At the center point of the angular input image, the gradual emergence of a corridor occurred. Subsequently, at the 60^{th} epoch, the establishment of the linkage between the corridor and the exterior wall was created. In general, a large bedroom was positioned along the angled facade of the form. Notably, there were attempts by the algorithm to divide this room in the process; however, complete wall formation was not developed (*epoch 150*). Along the same façade, in the final epoch, a master bathroom connected to the bedroom was generated next to the large bathroom. Conversely, on the orthogonal side, a spacious living area and an open kitchen were designed (Fig.9). Although some undefined wall and discontinuous space formations are observed, it can be interpreted that a generally defined floor plan has been generated.

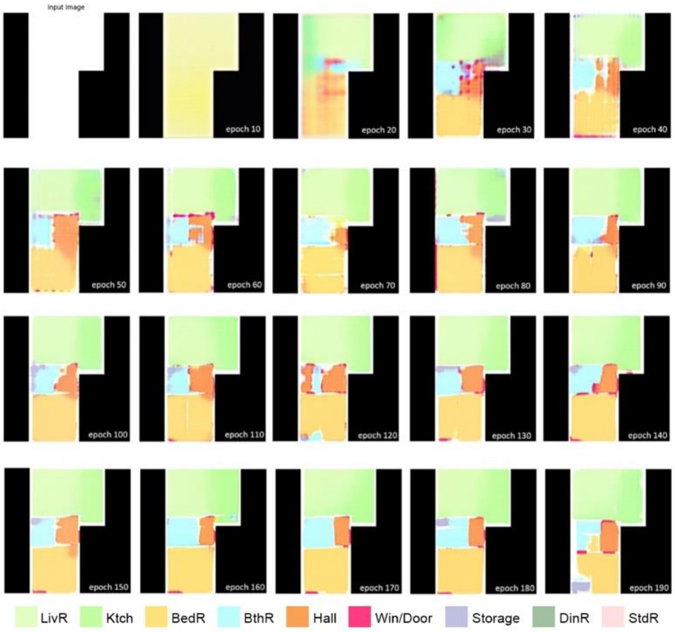


Figure 7. Generative results of orthogonal form with colored label descriptions representing space function

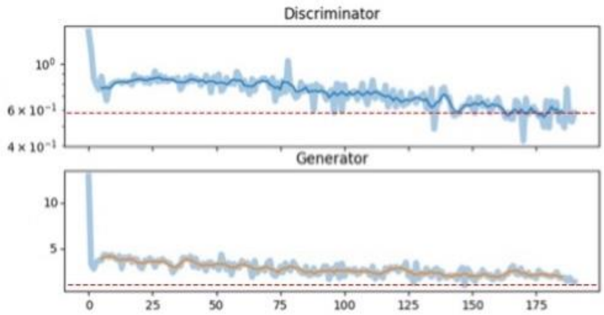


Figure 8. Loss function values of discriminator and generator networks of orthogonal model

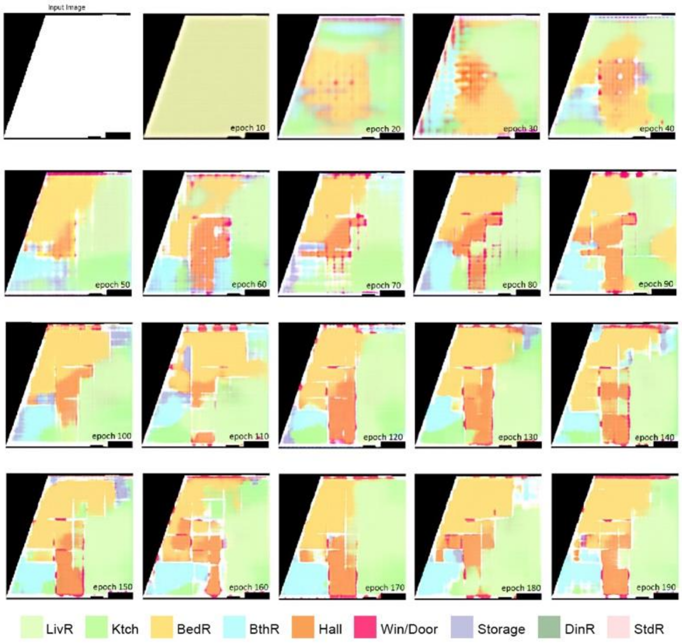


Figure 9. Generative results of angular form with colored label descriptions representing space functions

As determined by the computed loss functions, noticeable reductions in loss values were observed within both the generator and discriminator networks, indicative of progressive learning throughout the process. The discriminator loss was 0.55, while the generator loss was recorded at 1.66. Plots of the loss functions of the generator and discriminator networks during the procedure are visually presented in Figure 10.

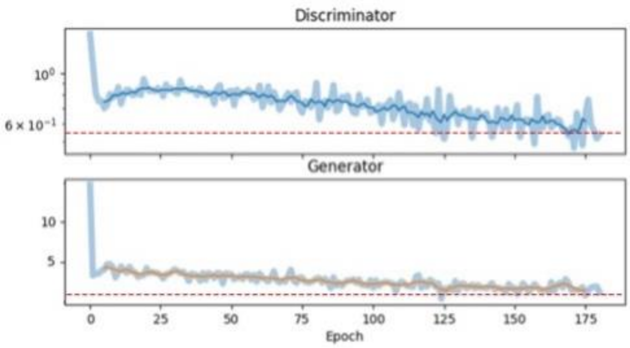


Figure 10. Loss function values of discriminator and generator networks of angular model

In the model, where an input image with a curvilinear form is selected, a corridor space positioned near the center of the form is observed during the production processes. Sleeping units, living room, kitchen and bathroom units are located around this space. Unlike other models, it is observed that more than one bedroom unit is generated. Another notable difference is the generation of the dining room space between living room and kitchen. In addition, color generations representing the study room unit were carried out in the last epochs. There are some problems such as loss of corridor continuity with the intervening storage unit (Fig 11). The discriminator loss achieved a measure of 0.71, while the generator loss was recorded at 1.89 (Fig.12)

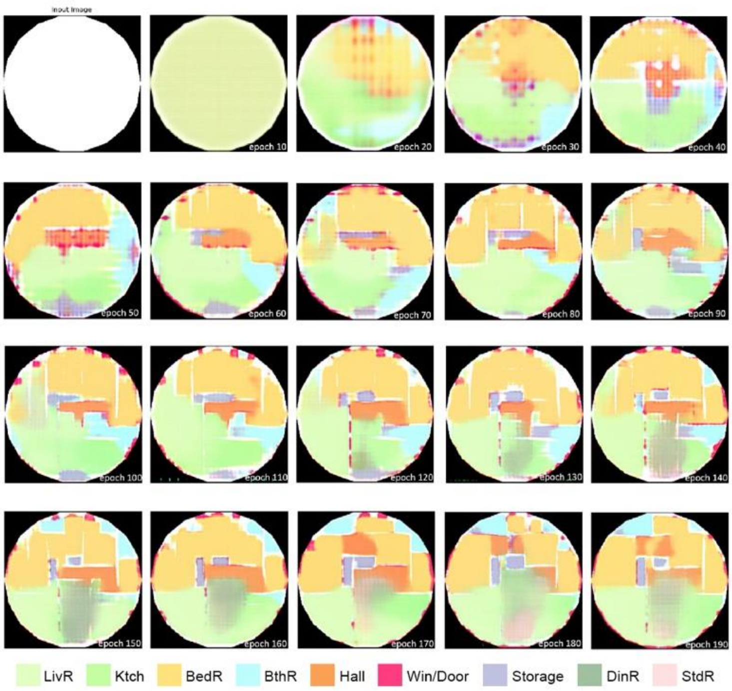


Figure 11. Generative results of circular form with colored label descriptions representing space functions

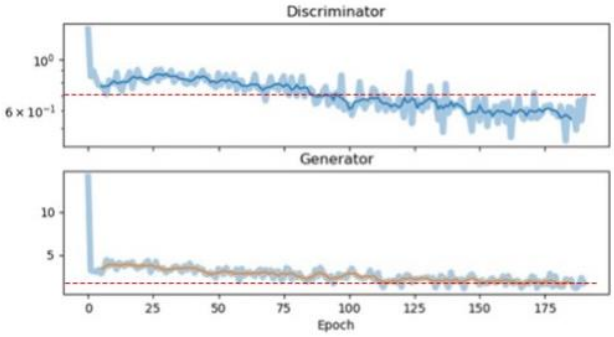


Figure 12. Loss function values of discriminator and generator networks of circular model

5. Evaluation and Discussion

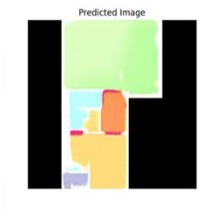
The less deterministic and more holistic character of artificial intelligence methods undoubtedly provides an advantage for its use in architecture. This paper presents case studies for multiple forms on the pixel-based architectural floor plan generation model. Although there are many accepted GAN algorithm evaluation methods in the literature, it is still a question to be answered whether those methods can be used in the evaluation of the outputs consisting of architectural floor plan schemes. Regarding the evaluation methods, it is concluded that if the performance of the GAN algorithm is efficient, the results are also efficient; however, evaluating the generations is a different statement from evaluating the performance of the algorithm for architectural design problems. It should be discussed whether the efficient performance of the algorithm in the generation of architectural plans means that it always produces an acceptable architectural floor plan or not. This is because floor plans contain semantic information that represents many spatial relationships.

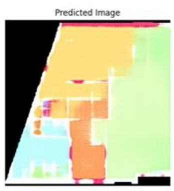
When the result images are examined, it is seen that all the places that should be included in the plan, such as the living room, kitchen, bedroom, bathroom, are present in the generated images. The outcomes were analyzed in terms of function-area distribution and were graphed in percentage terms (Fig. 13). Consistently, the living room and bedroom spaces occupy the most substantial spatial proportions, aligning with expected conventions. Minimizing the circulation area is one of the important objectives in the floor plan generation problem and it is noteworthy that unnecessarily long corridors were not observed in the generation outcomes. Particularly, the angular plan exhibited the highest circulation area among the various configurations considered. This highlights the importance of considering architectural geometry and layout in the analysis of circulation areas in different floor plan configurations.

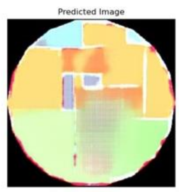
Figure 13. Function-area distribution analysis of generated floor plans

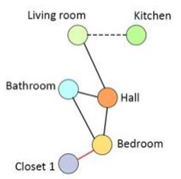
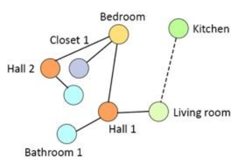
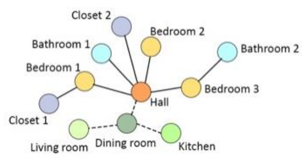
Evaluating the topological relationships of the floor plan areas generated by the algorithm is a multifaceted task that includes evaluating the connectivity, adjacency and spatial relationships between different functional areas within the layout. The output images have been transformed into a graphical representation where rooms and spaces are nodes and the connections between them (doors, openings, corridors) are edges (Table 2). The plans were evaluated comparatively according to different criteria determined. These can be listed as entrance recognition, natural lighting, spatial distribution logic, circulation efficiency and proportion of spaces.

TABLE 2. Evaluation of the topological relationships of the generated floor plans with comparative analysis criteria







<table>
<tr><th></th><th>Orthogonal</th><th>Angular</th><th>Circular</th></tr>
<tr><td>Criteria</td><td>
</td><td>
</td><td>
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Entrance recognition	There is no door representation in hall	There is entrance door representation connected to hall	There are doors/windows that can define the open access from living room
Natural light and ventilation	There is no window/door representation in outer edge of the plan	There are large windows only in the bedroom. Missing in common area and bathroom	There are large windows in common areas such as the living room and kitchen. Window-colored pixels are also observed on the exterior of bedrooms
Spatial distribution logic	Common spaces and private spaces are separated from each other	The connection between the kitchen and the bedroom is problematic, there must be a wall in between.	The upper half of the geometry can be interpreted as private, and the lower half divided by common areas
Circulation efficiency	Circulation was minimized with the corridor placed in the center of the geometry.	Access to all spaces is provided through the corridor connected from one edge center of the geometry.	A winding corridor was formed due to the geometric form and 3-bedroom configuration, continuity interrupted by closet
Proportion of spaces	The spaces seem to be of appropriate size.	The bedroom looks too large. It can be partitioned.	The bathroom represented at the top right may be too small for its use function.

6. Conclusion

Spatial configurations represent the dynamic interaction of spaces where they define unique spatial experiences. In the architectural context, spatial ambiguity is considered an architecturally intentional quality that enhances subjective user experience, especially in open, flexible plan designs. While existing models are primarily based on defined topological relationships, although topological relationships based on physical proximity are very important, especially in open, flexible plans that allow multiple uses, they alone do not fully reflect the complexity of the architectural space. In the study, it was shown that deep learning algorithms used visual relations that are vital for architectural functions and whether it can decipher visual field relationships from training data, including physical relationships.

The novel approach involves creating floor plan images with gradient coloring, capturing the essence of flexible spatial arrangements and the resulting visual relationships. Leveraging computer vision, a subfield of artificial intelligence, the research proposes a new generation model by using the opportunity to express the cognitive mechanisms and domain knowledge found in architectural representations. It is undeniable that pixel-based generative models have limitations regarding the precision in image output. The limitations arise due to the inherent discrete nature of pixels. The output generated by pixel-based models is reliant on the granularity of the pixel grid, and this limitation impacts the capacity to accurately render fine details and nuanced features present in architectural drawings. However, the capabilities of generative deep learning algorithms allow architects to quickly explore numerous design variations and configurations that may not be practical to consider manually. These models should not be seen as "digital designers" but rather as an artificial assistant to support the designer. As a conclusion, while pixel-based generative models are valuable tools for exploring broad design possibilities, their limitations in faithfully generating precise architectural details and complex spatial relationships should be acknowledged.

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THE DESIGN PROCESS WORKFLOW BETWEEN ROBOTICS METHODOLOGY AND ARTIFICIAL INTELLIGENCE TOWARD OPTIMUM DIGITAL FABRICATION

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Abstract. Industrial robots and artificial intelligence in design and construction have rapidly transformed the architecture industry in recent years, offering revolutionary opportunities which intern change the execution methods of buildings. This paper explores how implementing robotics methodology and AI in the design process can improve efficiency and accuracy, especially in generating scripts and data. It highlights their benefits and explores the challenges that must be addressed to optimize their use. It also automates specific tasks in the design process, such as model production and streamlining workflow; it is being used to produce intricate prototypes that manipulate materials and shapes that were previously difficult to create. It can produce more complex designs and achieve higher precision and accuracy in their work. Additionally, robotic arms can be programmed to perform repetitive tasks, freeing designers' time for more creative work. Integrating AI into the design process will bring new possibilities for architects to generate and evaluate a wide range of design options more quickly than before, where AI algorithms can analyze data from various sources, including user feedback and environmental data, to create design proposals that meet specific requirements. Also, AI can generate design scripts, providing robotics with infinite tasks. Hence, this research demonstrates the entire computational process, starting from the AI design phase and ending with robotic fabricated products. It explains the importance of embedded intelligent input into the algorithmic design process, enhancing these processes with infinite data and exploring the capability of the direct connectivity between the AI and robotic tasks monitoring to achieve the optimum solution for a specific product. As a result, the research will emphasize these processes' fully documented phases, demonstrating the importance of integrating AI and robotics arm into computational design and fabrication methodologies to enhance the architecture and construction industries for more performative and optimized strategies, providing new tools and methods to create buildings more efficiently. Furthermore, it reduces waste and minimizes errors. Additionally, integrating robotics and AI in fabrication can reduce the overall construction time and costs, making it more feasible for architects to create innovative and sustainable buildings.

Keywords: *Robotics, Design Process, Artificial Intelligence, Digital Fabrication, Python.*

ملخص. لقد أحدثت الروبوتات الصناعية والذكاء الاصطناعي في التصميم والبناء تحولًا سريعًا في صناعة الهندسة المعمارية في السنوات الأخيرة، حيث قدمت فرصًا ثورية أدت إلى تغيير أساليب تنفيذ المباني. تستكشف هذه الورقة كيف يمكن لتطبيق منهجية الروبوتات والذكاء الاصطناعي في عملية التصميم أن يحسن الكفاءة والدقة، خاصة في إنشاء البرامج النصية والبيانات. ويسلط الضوء على فوائدها ويستكشف التحديات التي يجب معالجتها لتحسين استخدامها. كما أنه يقوم بأتمتة مهام محددة في عملية التصميم، مثل إنتاج النماذج وتبسيط سير العمل؛ يتم استخدامه لإنتاج نماذج أولية معقدة تتعامل مع المواد والأشكال التي كان من الصعب إنشاؤها في السابق. ويمكنها إنتاج تصميمات أكثر تعقيدًا وتحقيق دقة ودقة أعلى في عملها. بالإضافة إلى ذلك، يمكن برمجة الأذرع الآلية لأداء مهام متكررة، مما يوفر وقت المصممين لمزيد من الأعمال الإبداعية. سيؤدي دمج الذكاء الاصطناعي في عملية التصميم إلى توفير إمكانيات جديدة للمهندسين المعماريين لإنشاء وتقييم مجموعة واسعة من خيارات التصميم بسرعة أكبر من ذي قبل، حيث يمكن لخوارزميات الذكاء الاصطناعي تحليل البيانات من مصادر مختلفة، بما في ذلك تعليقات المستخدمين والبيانات البيئية، لإنشاء مقترحات تصميم تلبي احتياجات التصميم. متطلبات محددة. كما يمكن للذكاء الاصطناعي إنشاء نصوص تصميمية، مما يوفر للروبوتات مهام لا حصر لها. ومن ثم، يوضح هذا البحث العملية الحسابية بأكملها، بدءًا من مرحلة تصميم الذكاء الاصطناعي وانتهاءً بالمنتجات الروبوتية المصنعة. ويشرح أهمية المدخلات الذكية المضمنة في عملية التصميم الخوارزمي، وتعزيز هذه العمليات ببيانات لا حصر لها واستكشاف قدرة الاتصال المباشر بين الذكاء الاصطناعي ومراقبة المهام الروبوتية لتحقيق الحل الأمثل لمنتج معين. ونتيجة لذلك، سيؤكد البحث على المراحل الموثقة بالكامل لهذه العمليات، مما يدل على أهمية دمج الذكاء الاصطناعي وذراع الروبوتات في التصميم الحسابي ومنهجيات التصنيع لتعزيز صناعات الهندسة المعمارية والبناء من أجل استراتيجيات أكثر أداء وتحسينًا، وتوفير أدوات وأساليب جديدة لتحسين الأداء. إنشاء المباني بشكل أكثر كفاءة. علاوة على ذلك، فهو يقلل من الهدر ويقلل من الأخطاء. بالإضافة إلى ذلك، يمكن أن يؤدي دمج الروبوتات والذكاء الاصطناعي في التصنيع إلى تقليل الوقت والتكاليف الإجمالية للبناء، مما يجعل إنشاء مباني مبتكرة ومستدامة أكثر جدوى للمعماريين.

الكلمات المفتاحية: *علم الروبوتات، العملية التصميمية، الذكاء الاصطناعى، التصنيع الرقمى، لغة برمجة بايثون.*

1. Introduction

The seamless integration of robotics methodology and artificial intelligence (AI) has brought forth transformative advancements in the field of digital fabrication. This interdisciplinary convergence has created intricate and sophisticated 3D models that were once considered beyond the realm of possibility. In this paper, we embark on an exciting journey that seeks to explore the symbiotic relationship between Robotics and AI, mainly focusing on AI Recent Platform's role in generating diverse 3D models for subsequent fabrication using robotic arms.

The union of robotics and AI has ushered in a new era of digital fabrication efficiency, accuracy, and inventiveness. Manufacturing and production operations have long been based on robotics technologies, notably robotic arms. These have proven essential instruments in various industries, from the automobile to aerospace and beyond, thanks to their precise and programmable actions. Robotic arms' full potential, meanwhile, only emerges when paired with AI systems' cognitive skills (Philip F. Yuan · Hua Chai · Chao Yan · Keke Li ·Tongyue Sun, 2022).

At the heart of our exploration lies the innovative Chat GPT (Generative Pre-trained Transformer) technology, a state-of-the-art AI language model. Its ability to generate human-like responses and understand complex instructions has revolutionized how humans interact with machines. By leveraging AI Prompts, we can communicate our design ideas and specifications more effectively with robotic systems, enabling a streamlined and intuitive design process (OPENAI, 2023).

Furthermore, our investigation delves into the concept of Stable Diffusion, a cutting-edge AI technique that facilitates the generation of high-quality images. By utilizing this tool, we aim to harness the power of AI to produce visually appealing images that can provide vital guidance in crafting a diverse array of 3D models (Mohamed Diab, Julian Herrera, Musical Sleep, Bob Chernow, Coco Mao, 2022).

This paper aims to elucidate the design process workflow that arises from the harmonious interplay between Robotics Methodology and AI. We endeavor to showcase how this innovative synergy fosters an environment where designers and engineers can collaboratively interact with robotic systems, imbuing them with creative intent and yielding unparalleled possibilities in digital fabrication.

Through a series of case studies and practical demonstrations, aiming to shed light on the transformative potential of deep learning platforms in enhancing the 3D model generation process. By harnessing designers' creative insights, AI's computational prowess, and robotic arms' precision, we can fabricate intricate and personalized designs with remarkable efficiency and accuracy.

In conclusion, the amalgamation of Robotics Methodology and Artificial Intelligence is poised to redefine the scene of digital fabrication. Our exploration of the design process workflow, centered around Chat GPT and Stable Diffusion, underscores the significance of this integration, empowering us to unleash the full potential of 3D model generation for myriad applications. As we embark on this transformative journey, we look forward to uncovering new vistas of possibilities where human ingenuity, AI intelligence, and robotic precision converge in a harmonious symphony of creation.

2. Workflow Toward Optimum Digital Fabrication

Figure 1 encapsulates a comprehensive journey, illuminating the intricate stages that transform conceptualization into a tangible reality. The workflow unfolds with Chat GPT4's creative ideation, sparking initial design concepts. These concepts are refined through stable diffusion, harnessing AI's artistic prowess. Python coding breathes life into the design within Rhino 3D and Grasshopper, endowing it with intricate geometry. The next stage employs PhysX for dynamic simulations, ensuring structural integrity. Integration of the Robot Plugin in Grasshopper orchestrates the design's interaction with robotic systems. Machina.NET takes the baton, seamlessly executing commands for fabrication. Finally, these orchestrated steps culminate in a physical model, as realized in the final output. This figure maps the convergence of cutting-edge technologies, artistic innovation, computational precision, and robotic automation, showcasing the transformative journey from inception to realization.

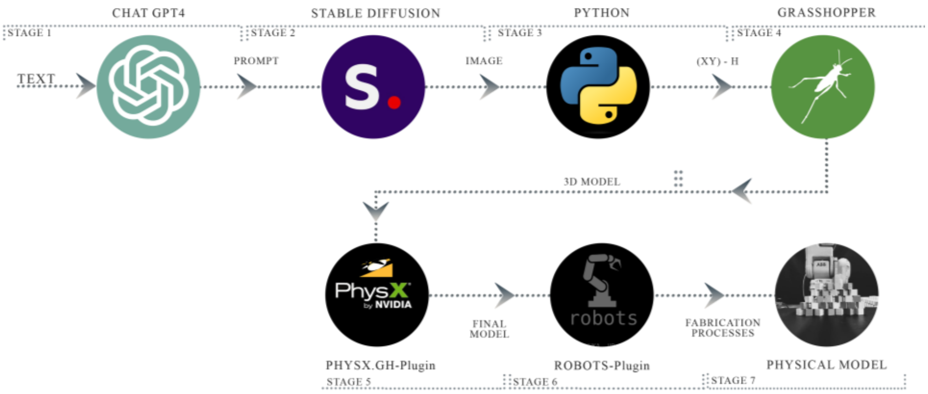

Figure 1. Workflow Stages from Design to Digital Fabrication (By author, 2023).

2.1. STAGE 1 GENERATING PROMPT FROM CHAT GPT4

ChatGPT 4 is a ground-breaking invention that epitomizes the power of human-machine interaction at the forefront of artificial intelligence. Building on its predecessors, It demonstrates an impressive capacity for text input, understanding complex prompts, and producing coherent and contextually relevant text outputs in response (OpenAI, 2023).

This sophisticated language model redefines the limits of AI's linguistic capabilities by providing a dynamic and adaptable tool that can easily engage in discussions, give insightful information, and aid in problem-solving (OpenAI, 2023).

It opens a world of possibilities with its ability to comprehend complex commands and produce human-like writing, revolutionizing how we interact with computers and unlocking their potential in various fields (OpenAI, 2023).

The ChatGPT 4 contact, crucial to the procedure shown in Figure 2, includes giving the model textual input. The prompt wording is precisely created to capture the core of the discussion or job at hand using this input as its basis. The prompt text acts as a transitional element between the user's first input and the succeeding stage of steady diffusion. It captures the user's context and purpose, facilitating a smooth workflow transition.

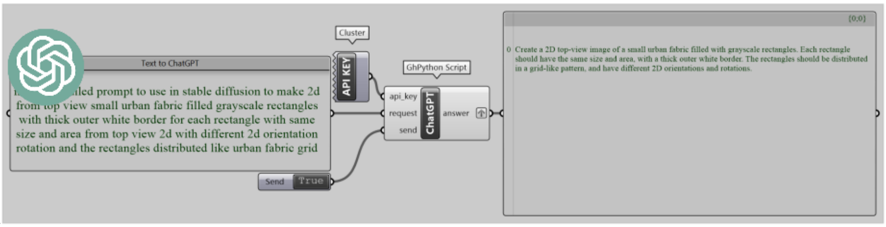

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Figure 2. Chat GPT 4 Text to Prompt Text (By author, 2023).

The user's inquiry is then refinedly embodied in this prompt text. It is subsequently directed into the stable diffusion stage, the anchor for more investigation and augmentation using AI-based processes. This iterative process underscores the dynamic interplay between initial text input, AI's understanding, prompt generation, and the subsequent stages, harmonizing these elements into a coherent and effective pipeline.

2.2. STAGE 2 TEXT TO IMAGE GENERATION

Stable Diffusion offers an open-source text-to-image model that transcends conventional limitations, making it a ground-breaking development in AI-powered creativity. This invention instantly turns written explanations into beautiful visuals by fusing language and flair. Stable Diffusion ushers in a brand-new era of creative expression and imaginative synthesis with its remarkable ability to cross the gap between words and images. Utilizing AI overcomes the constraints of human creativity and enables the creation of fascinating and astounding graphics that ring true to the text's core (Mohamed Diab, Julian Herrera, Musical Sleep, Bob Chernow, Coco Mao, 2022).

As we delve into the capabilities of Stable Diffusion, we uncover a fusion of language and visual artistry that has the potential to redefine how we perceive, create, and interact with images (Mohamed Diab, Julian Herrera, Musical Sleep, Bob Chernow, Coco Mao, 2022).

Figure 3 illustrates a detailed procedure that begins with entering a text prompt. This prompt serves as the starting point for the Stable Diffusion model by embodying the user's creative intention. Dynamically integrated parameters, such as photo width, height, and the required number of output photographs, allow for customizing the generated images to exact requirements.

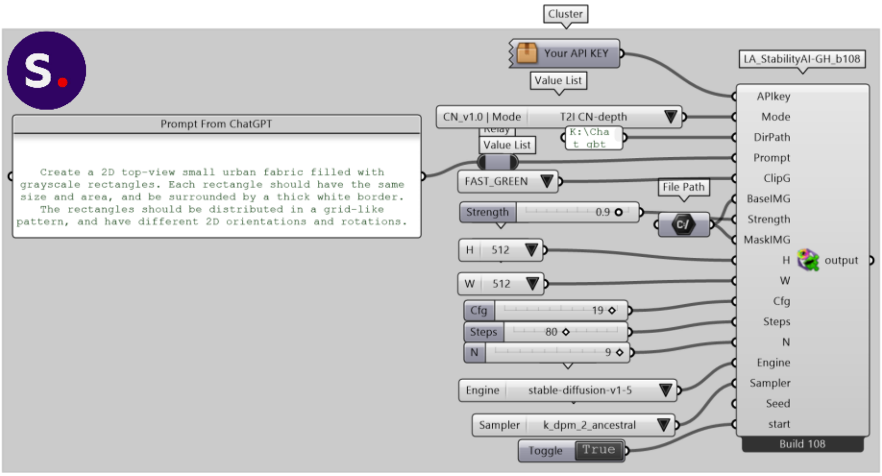

Figure 3. Text to image through Stable Diffusion AI plugin (By author, 2023).

Stable Diffusion uses its inherent knowledge of the prompt to synthesize a sequence of visuals, each an artistic interpretation in line with the given words, as the AI-driven process develops. The graphic also demonstrates how the output images' varying resemblance to the query's contextual framing (CFG). This dynamic spectrum of proximity reflects the model's capacity to dynamically strike a balance between originality and faithfulness to the original textual description. Through this intricately orchestrated process, Stable Diffusion crafts breathtaking visuals and maintains a unique connection to the user's intent, fostering an unparalleled synergy between text and image.

Figure 4 elucidates the output data generation and management process from Stable Diffusion. Upon completing the text-to-image transformation, a table details the essential attributes of each generated image. This table encompasses vital information such as the image's filename, dimensions (width and height), and the degree of proximity to the prompt's contextual framing.

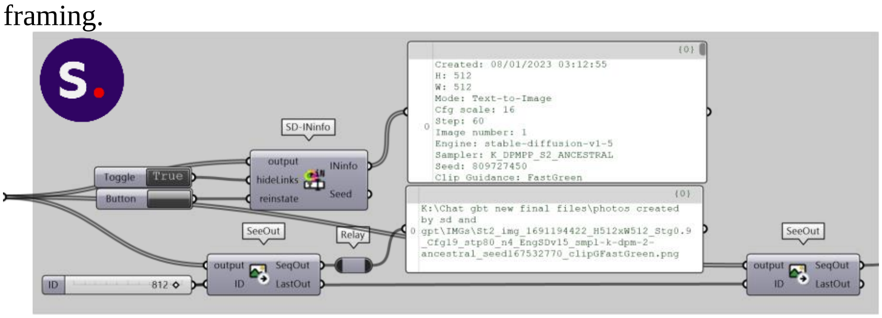

Figure 4. Output Data image from Stable Diffusion (By author, 2023).

These insights provide a comprehensive overview of the diverse image set produced by the model. The figure also highlights the saved location of these output images, demonstrating their organization in a designated repository or directory for easy access and management. This structured arrangement simplifies the retrieval of specific images. It fosters efficient integration into subsequent stages of the creative workflow, showcasing the model's ability to bridge the gap between AI-generated content and user-friendly implementation (Mohamed Diab, Julian Herrera, Musical Sleep, Bob Chernow, Coco Mao, 2022).

Figure 5 succinctly portrays the iterative process involving output images from Stable Diffusion. Through a series of trials, the model generates diverse images in response to the same text prompt, showcasing the versatility and creative potential of the AI system. Each trial results in a unique image that captures different aspects of the prompt's interpretation, contributing to a rich and varied output. This iterative approach exemplifies the dynamic nature of the AI-generated content, enabling users to explore a range of visual interpretations stemming from a single textual description.

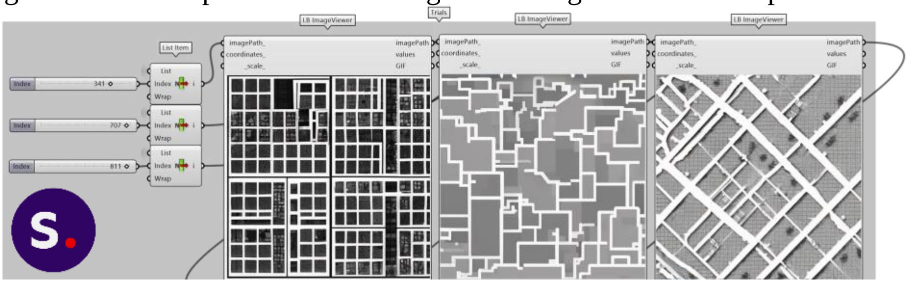

Figure 5. Output Trials from Stable Diffusion (By author, 2023).

2.3. STAGE 3 ANALYSIS IMAGE DATA USING PYTHON

Incorporating Python into Grasshopper creates an effective synergy between parametric design and sophisticated coding abilities. By utilizing Python's adaptability and computational capabilities, this dynamic collaboration enables designers, architects, and engineers to increase the functionality of Grasshopper (G.Wurzer, W.E.Lorenz, 2019).

Python scripting provides access to complicated algorithmic design, enabling users to process data and automate complex tasks precisely. In addition to improving Grasshopper workflow efficiency, this combination of parametric design principles and Python's coding capabilities makes it possible to create complex, data-driven designs beyond conventional limitations (G.Wurzer, W.E.Lorenz, 2019).

Figure 6 succinctly illustrates the transformation of AI-generated text output from ChatGPT 4 into functional Python code. The figure showcases a segment of the generated text, which encapsulates instructions for image processing. The code snippet outlines a process that entails identifying the centers and shapes within the image while also dynamically determining the heights of these centers based on color attributes.

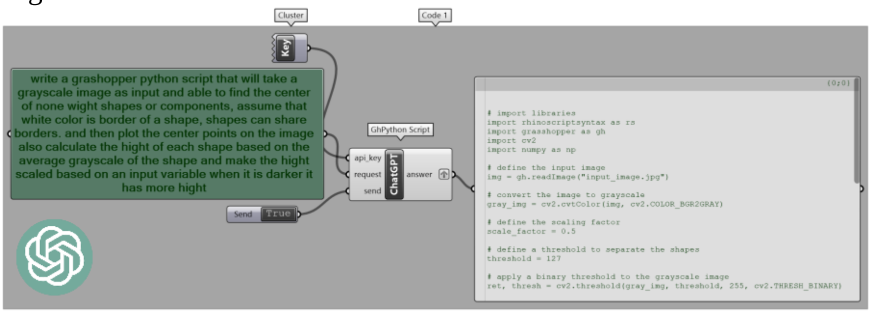

Figure 6. Python Code output from chat GPT 4 (By author, 2023).

The provided code in Figure 7 orchestrates a comprehensive image processing sequence focused on shape identification, center determination, and average grayscale value ("height") calculation. This intricate process unfolds through the following steps: essential libraries are imported to facilitate image analysis and manipulation; the image is loaded, bordered, and subsequently binarized for streamlined shape detection; dilation techniques are employed to identify internal shapes within the image; each of these shapes is meticulously labeled, and their respective centers are pinpointed, while concurrently calculating the average grayscale value to infer the "height" attribute; the results are efficiently cataloged within dedicated x, y, and h lists, and then promptly displayed. To maximize the effectiveness of this code, precise definitions for the placeholders 'image_p' and 'Pixelcolorrange' are requisite, ensuring seamless execution of the entire process.

Final Code 1

```
# -*- coding: utf-8 -*-
"""
Python Script
Created on  Friday August 2023 02:45:51
@author:  Mazen

[desc]
Description of the plugin Here
Write here any thing...
[/desc]

ARGUMENTS:
----------
<inp>
    _input :[required] - [type = int] - [default = None]
    Descripe your input here
        * bullet point.
        * bullet point
</inp>
<inp>
    Other inputs go here ...
</inp>

RETURN:
----------
    <out>
        output_ : indicate your output description here. \n refers to a new line.
    </out>

"""
#import rhinoscriptsyntax as rs
import sys
print (sys.prefix)
from PIL import Image
import numpy as np
import cv2
from scipy.ndimage import binary_dilation, label, center_of_mass, mean

# image path
image_path = image_p

# weight is 250 anything less than that will be considered shape
white_threshold = Pixelcolorrange

# useful if there are shape inside a shape
dilation_size = 1

# height scale factor
height_scale_factor = 1


def get_shape_centers():
    # Load grayscale image
    image = Image.open(image_path).convert('L')
    image = np.array(image)

    # Add a white border to the image
    image = cv2.copyMakeBorder(image, 10, 10, 10, 10, cv2.BORDER_CONSTANT, None, value=255)

    # Binarize the image -- assume anything not white is part of a shape
    shape_mask = image < white_threshold

    # Dilate the image and subtract from the original to get a mask that includes only the internal borders
    dilated = binary_dilation(shape_mask, iterations=dilation_size)
    internal_borders = dilated & ~shape_mask

    # Add the internal borders back to the original shape mask
    shape_mask_with_holes = shape_mask | internal_borders

    # Label each shape
    labels, num_shapes = label(shape_mask_with_holes)

    # Calculate the center of each shape
    centers = center_of_mass(shape_mask_with_holes, labels, np.arange(num_shapes) + 1)

    # Calculate the height (average grayscale value) of each component
    # Invert so darker pixels have higher height
    heights = (255 - mean(image, labels, np.arange(num_shapes) + 1)) * height_scale_factor

    return centers, heights


centers, heights = get_shape_centers()

x = []
y = []
h = []
for center, height in zip(centers, heights):
    print(center, height)
    x_, y_ = center
    # my_line = "({0}, {1}) {2}".format(x, y, height)
    x.append(x_)
    y.append(y_)
    h.append(height)

print(x, y, h)
```

Figure 7. Show the final python code to generate the centroid points (By author, 2023).

Figure 8 and Figure 9 succinctly capture the juxtaposition of outputs derived from Stable Diffusion and Python scripting. On the upside, a series of images generated by Stable Diffusion showcases diverse visual interpretations stemming from the same textual input. These images highlight the model's creative versatility and ability to produce captivating and unique visuals. On the downside, the figure showcases images resulting from the Python code's execution. In these images, shapes' centers are marked with vivid red dots, aligning with the algorithmic logic outlined in the code.

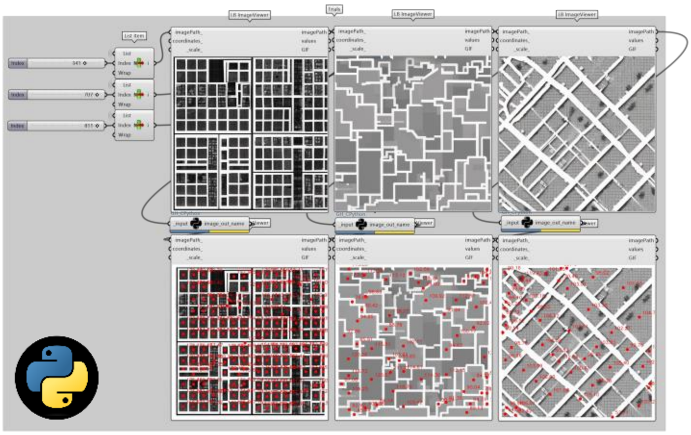

Figure 8. Output Images from Python Code with Shapes Centers (By author, 2023).

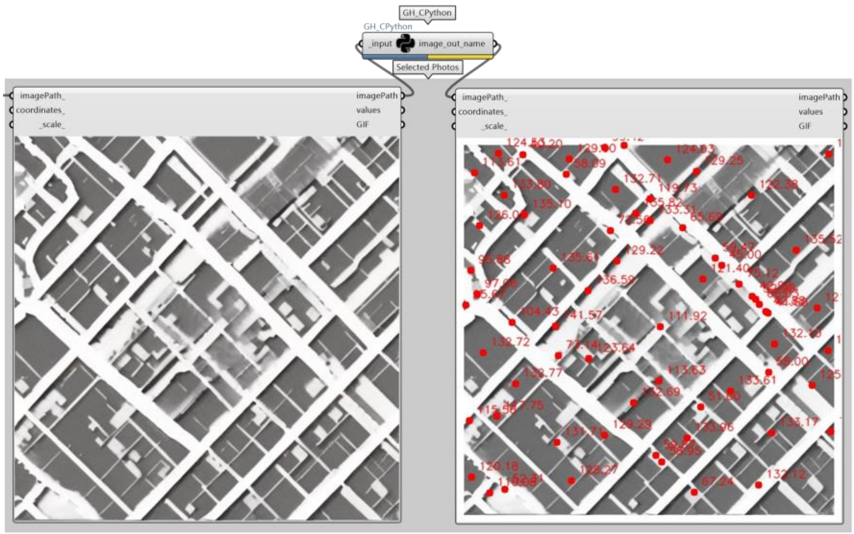

Figure 9. Final Output image from Python code (By author, 2023).

Figure 10 succinctly illustrates the extraction of essential data from images to create points and height values. The process involves analyzing the images to derive X and Y coordinates that define the positions of points. These coordinates act as anchors, establishing the spatial distribution of the points within the image. Additionally, the figure emphasizes the extraction of height values that correlate with color attributes. Translating color information into height introduces a multi-dimensional aspect to the points, enriching the visualization with depth and context. This figure underscores the intricate integration of image analysis and data processing, transforming visual information into actionable numerical data that is the foundation for subsequent design and fabrication stages.

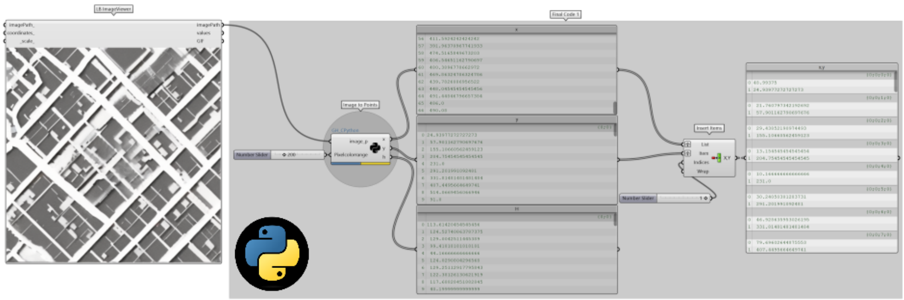

Figure 10. Show the output data from python code (x, y, h) values (By author, 2023).

2.4. STAGE 4 GENERATING 3D MODEL USING GRASHOPPER

Grasshopper is an innovative and influential visual programming language within design and architecture. Developed as an extension for Rhino 3D, Grasshopper introduces a paradigm shift by enabling designers, architects, and engineers to create complex parametric models through a visual interface (Bachman, 2017).

This unique approach emphasizes algorithmic design, offering a canvas where users manipulate graphical components to define relationships and generate intricate geometries. Grasshopper's intuitive nature bridges the gap between programming and design, democratizing computational design concepts and unlocking the potential for limitless creative exploration (Bachman, 2017).

The illustrated sequence succinctly depicts the seamless transition of output data from the Python code, as portrayed in Figure 11, to the generation of precise points within the Rhino 3D program, as showcased in Figure 12. The extracted data, comprising coordinates and height attributes.

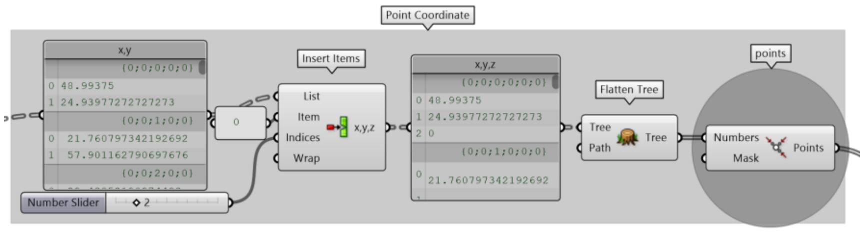

Figure 11. Grasshopper script that transfers Python data to points (By author, 2023).

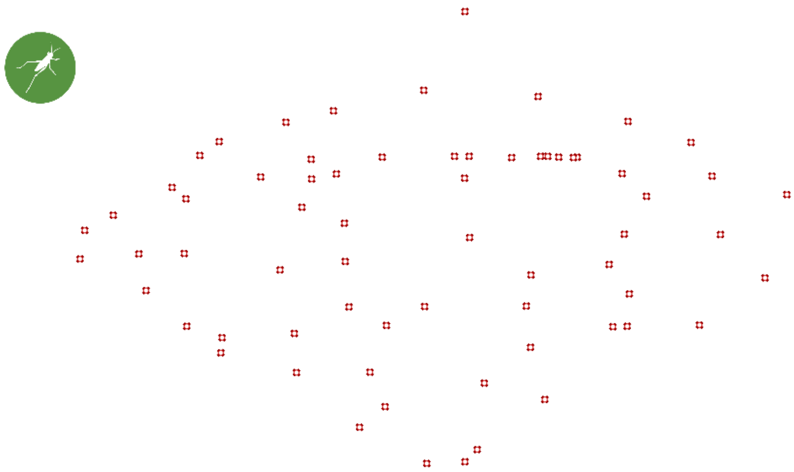

Figure 12. Generated points From Python Output Data (By author, 2023).

Figure 13 shows how the illustrated sequence effectively depicts a crucial change in the workflow. The created points here are seamlessly integrated into the following Python code. To prevent any collisions between the 3D cubes, this crucial stage is a thorough process where the points are carefully analyzed to find and delete any instances of intersection.

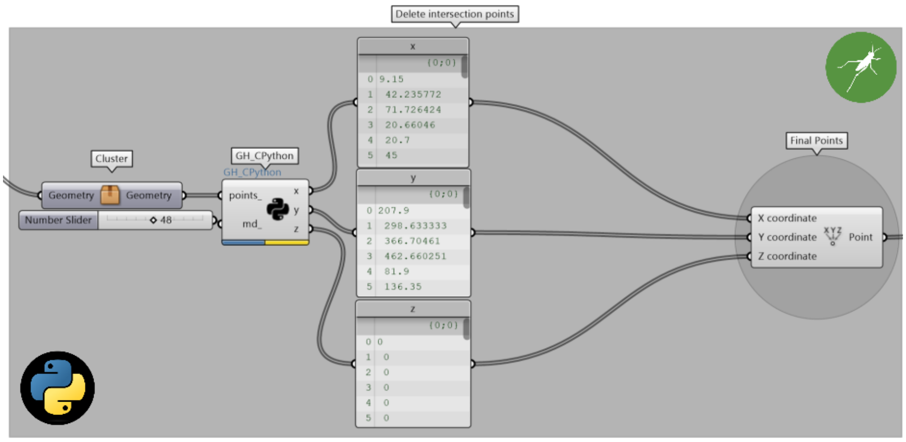

Figure 13. Grasshopper Script shows the process of deleting any intersection points (By author, 2023).

The Python software skillfully evaluates the spatial relationships between these points and removes any that could result in overlaps. This approach results in the final set of refined points, as seen in Figure 14.

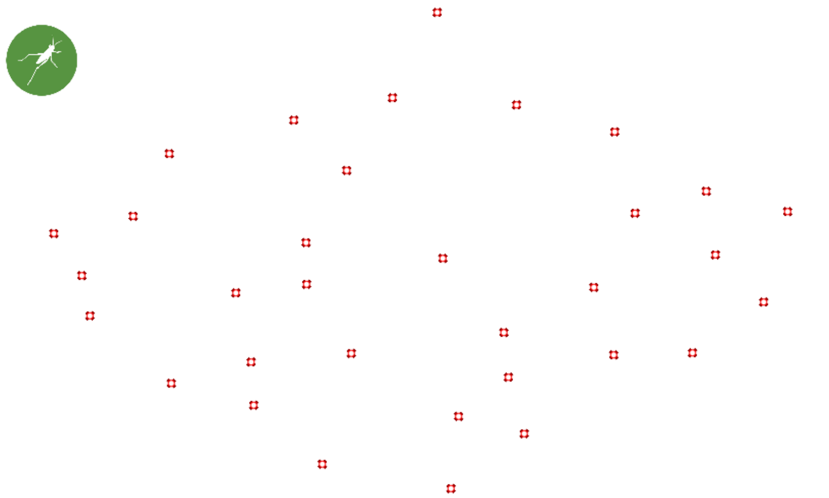

Figure 14. Final Points Generated from Python Code (By author, 2023).

Figure 15, the script ingeniously transforms the finalized points into boxes, strategically positioning them as the centers of the structures. The boxes bear a uniform dimension of 35 millimeters, as indicated.

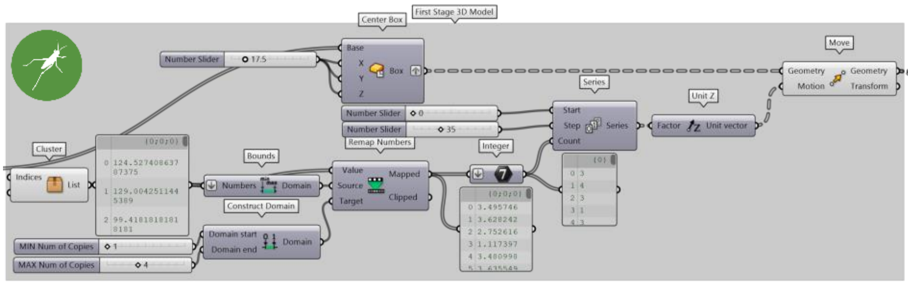

Figure 15. Grasshopper script for making 3D Boxes (By author, 2023).

As the narrative advances to Figure 16, the design springs to reality, with the boxes beautifully realized in the digital space. The following step in Figure 17 manifests a brilliant replication strategy: the boxes are duplicated vertically; the extracted color values from the image determine their count. In a masterful touch, these values are remapped to govern the vertical copies' height and quantity, resulting in a dynamic composition that elegantly balances design aesthetics and computational precision.

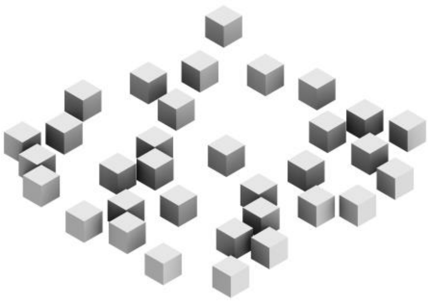

Figure 16. 3D boxes generated from the final points (By author, 2023).

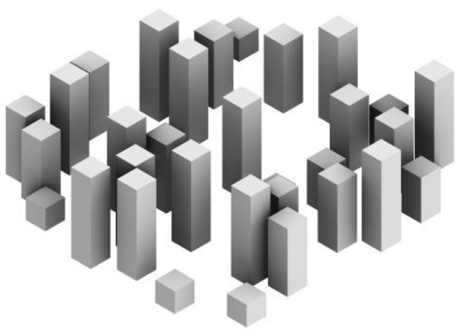

Figure 17. Generated Boxes after adding the height value (By author, 2023).

A curve attractor is added to a rotational transformation in Figure 18 for the script. The shapes exhibit an incredible diversity because of this combination of approaches. The outcome—a compelling variety of shapes that dynamically react to the effect of the curve attractor—comes into being as the tale progresses to Figure 19.

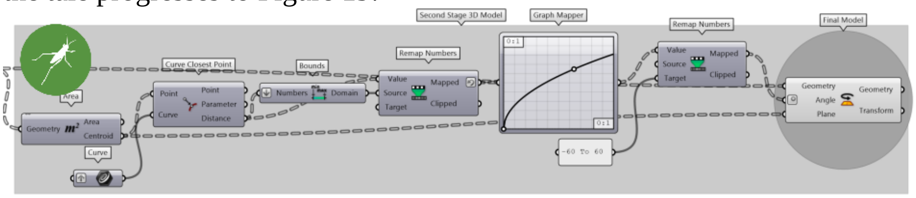

Figure 18. Grasshopper script shows the rotation of boxes by curve attractor (By author, 2023).

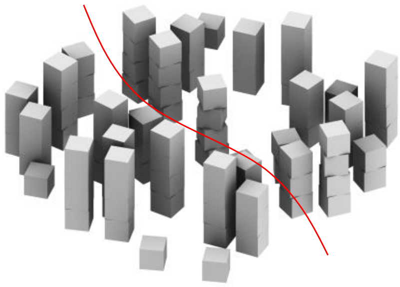

Figure 19. Final 3D model of Boxes (By author, 2023).

2.5. STAGE 5 3D MODEL STABILITY

PhysX.GH represents a groundbreaking advancement in computational design and simulation, revolutionizing the capabilities of Grasshopper (Kao, 2019). Developed as an extension for Grasshopper, PhysX.GH integrates NVIDIA's PhysX engine, renowned for its prowess in physics-based simulations, into parametric modeling (Kao, 2019). This fusion of cutting-edge physics simulation with Grasshopper's intuitive interface opens new avenues for architects, engineers, and designers to explore the dynamic behaviors of structures, materials, and environments (NVIDIA, 2021). PhysX.GH empowers users to incorporate real-world physics into their designs, fostering a deeper understanding of complex interactions and enabling the creation of innovative, responsive structures (NVIDIA, 2021).

Figure 20 shows this essential stage, which entails utilizing PhysX.GH to simulate the model's dynamic behavior and assess its stability under various circumstances. The design can be subjected to forces and interactions in the real world because of the script's excellent integration of parametric modeling and physics-based simulation principles.

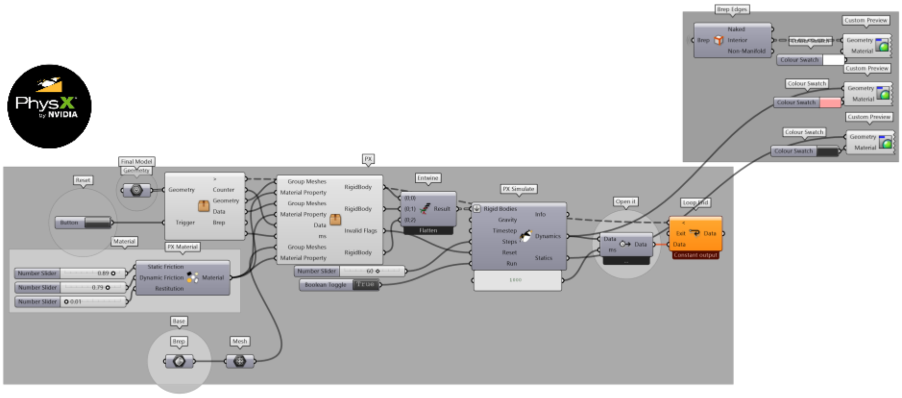

Figure 20. Grasshopper script shows the script of test PhysX on the 3D model (By author, 2023).

The PhysX plugin activates, actualizing the simulation process as the narrative in Figure 21 progresses. The plugin carefully examines the stability of the model using complex computations, demonstrating that the design is remarkably durable and well-suited for production.

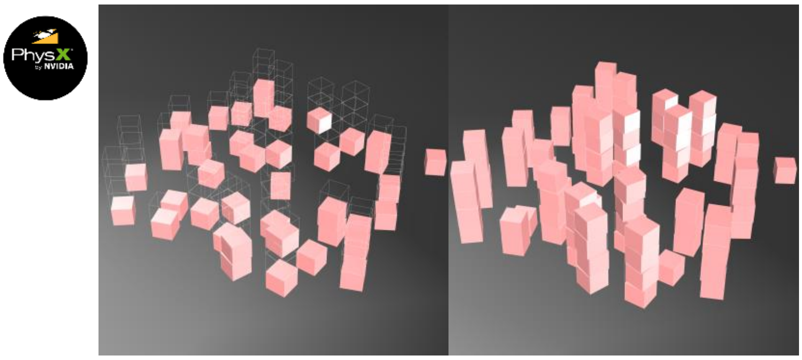

Figure 21. Show the simulation of PhysX plugin to the final model (By author, 2023).

2.6. STAGE 6 SIMULATE ROBOTIC ARM DIGITAL FABRICATION

The world of architectural and design automation is given a startling new dimension with the Robot Plugin for Grasshopper. This plugin, created as an add-on for Grasshopper, effortlessly incorporates robotic programming and control into the design workflow (Visose, 2022).

By making it possible to develop and optimize robotic processes right inside the Grasshopper environment, it gives architects, designers, and engineers the power to close the gap between digital design and physical manufacture. Users of the Robot Plugin can investigate cutting-edge applications of robotic arms for work like material manipulation, assembly, and fabrication (Visose, 2022).

Figure 22 shows the Grasshopper script that makes choosing a certain kind of robotic arm for integration easier. The script enables easy importation of the Iaac-IRB140 robotic arm model into the Grasshopper environment.

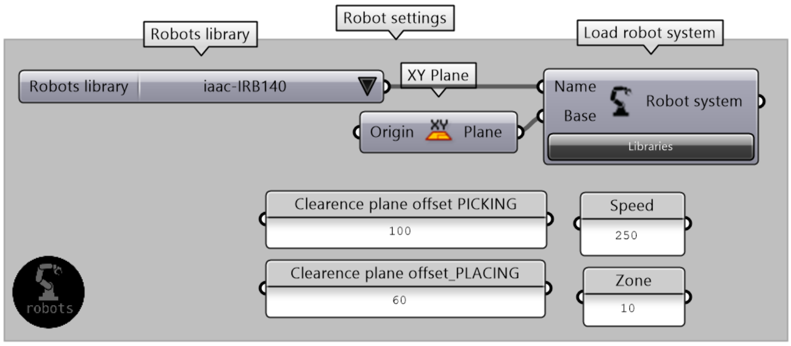

Figure 22. Grasshopper Script shows the selection of the type of robotic arm (By author, 2023).

Figure 23 showcases the Grasshopper script that facilitates the seamless integration of a pick and place tool into the selected robotic arm for simulation purposes. This integration sets the stage for a sophisticated interplay between the tool and the robotic arm's capabilities. As the narrative advances to Figure 24, the form of the imported tool is unveiled, revealing a visual representation of the integrated tool's design.

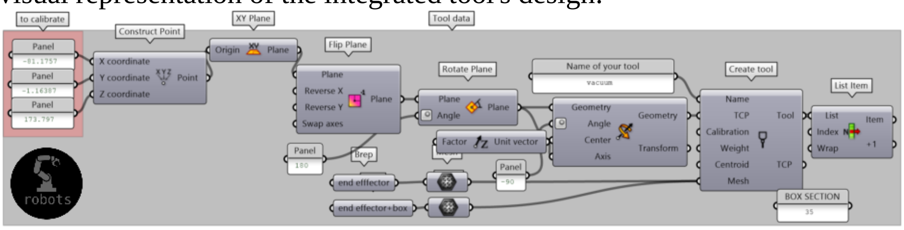

Figure 23. Grasshopper Script shows the importing tool to Robotic arm (By author, 2023).

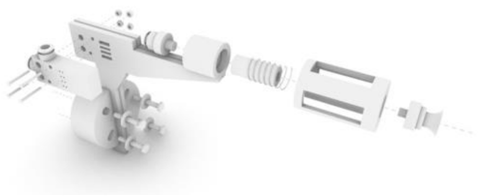

Figure 24. Pick and Place Tool that is connected to the robotic arm (*Mayor, 2023).*

Figure 25 presents the Grasshopper script responsible for specifying the exact position of the stack of boxes in a clear but crucial way. This script carefully sets up the spatial parameters in the Grasshopper environment, accurately replicating how the boxes are arranged before processing begins.

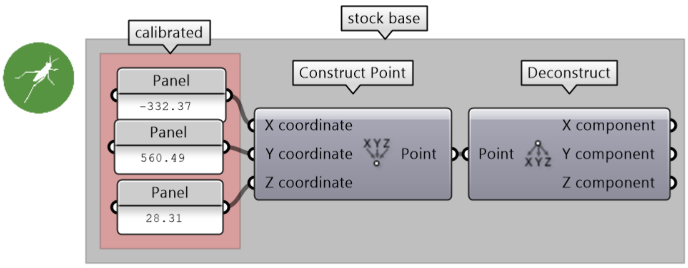

Figure 25. Grasshopper Script shows the location of Stock of Boxes to be used in fabrication (By author, 2023).

Figure 26 succinctly captures a pivotal step in the process, showcasing the Grasshopper script responsible for extracting planes from the boxes. This operation holds paramount significance as the robotic arm operates based on planes for precise object placement. By extracting these planes, the script establishes a foundational framework that seamlessly aligns the boxes with the robotic arm's operational logic, underscoring the intricate coordination between digital design and robotic execution.

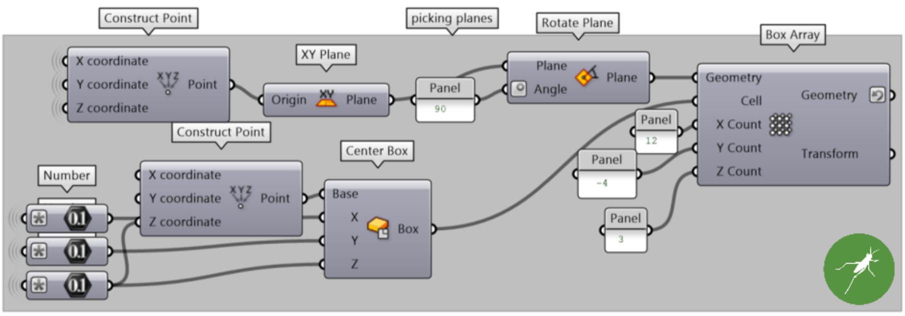

Figure 26. Grasshopper Script shows the extraction of boxes planes (By author, 2023).

Figure 27 reveals the Grasshopper script that meticulously sorts the extracted planes in the Z direction. This strategic sorting enhances the robotic arm's fabrication process by ensuring an organized and sequential placement of objects. As the narrative progresses to Figure 28, the sorting continues, arranging the planes per row. Finally, in Figure 29, the script adeptly arranges the planes in the Y direction, further streamlining the pathway for the robotic arm's operation.

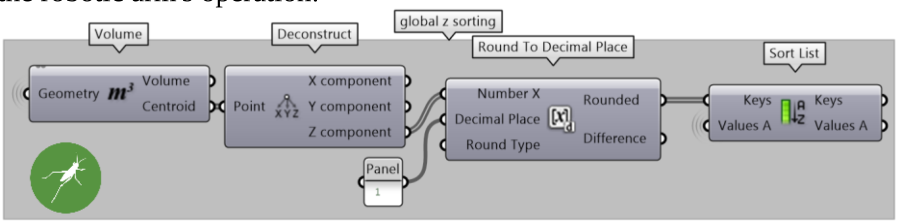

Figure 27. Grasshopper Script shows the sorting the planes in Z direction (By author, 2023).

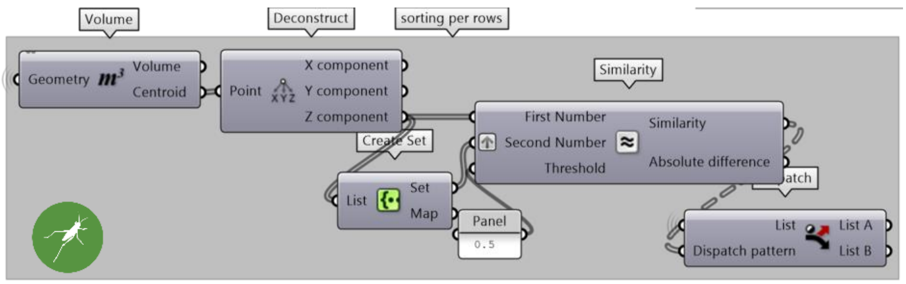

Figure 28. Grasshopper Script shows the sorting the planes per Rows (By author, 2023).

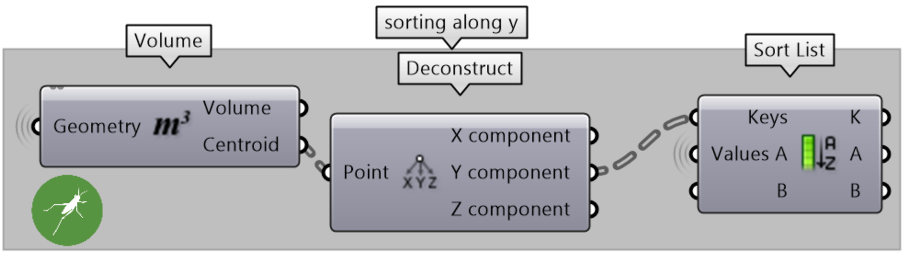

Figure 29. Grasshopper Script shows the sorting of the planes in y direction (By author, 2023).

Figure 30 reveals the Grasshopper script that outlines the simulation process and generates the output code necessary to initiate the fabrication phase. The script bridges the gap between digital simulation and tangible fabrication, setting the stage for seamless execution.

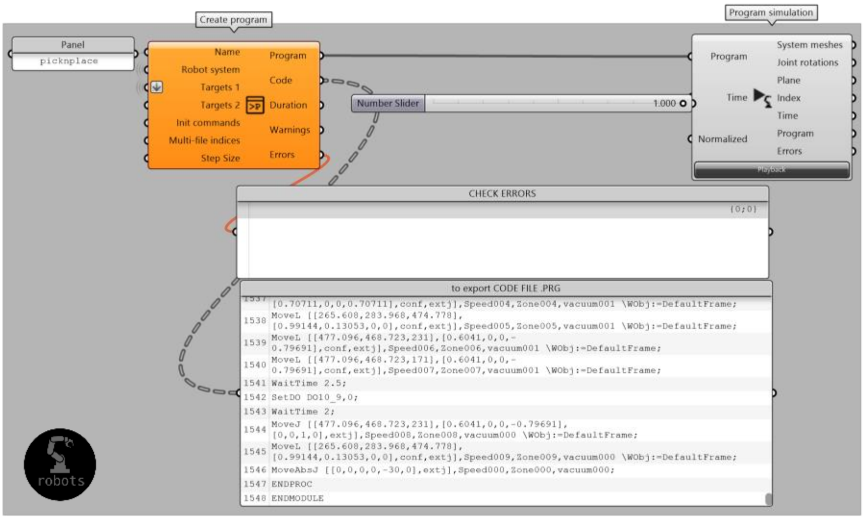

Figure 30. Grasshopper Script shows the script of the simulation of robotic arm (By author, 2023).

Figure 31 meticulously illustrates the fabrication process steps as the boxes are systematically positioned. Finally, in Figure 32, the simulation culminates in a compelling visual representation, where all boxes have been precisely placed in their designated origins. These figures collectively encapsulate the plugin's power in orchestrating a holistic design-to-fabrication journey, merging the virtual and the physical with remarkable cohesion.

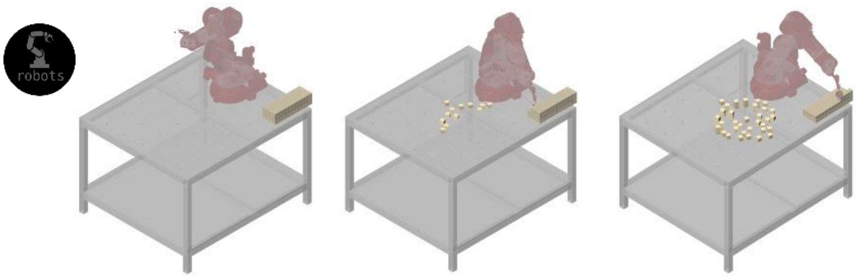

Figure 31. simulation stages of pick and place boxes (By author, 2023).

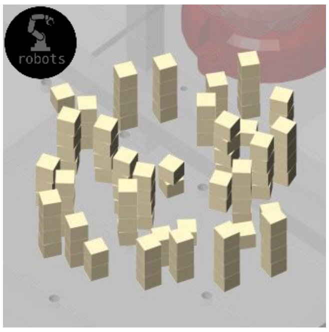

Figure 32. Final simulation with all boxes placed correctly (By author, 2023).

2.7. STAGE 7 DIGITAL FABRICATION MODEL IN REAL WORLD

Machina.NET stands as a pioneering force within robotic control and automation, offering a comprehensive platform for orchestrating robotic systems' precise movements and actions. Developed as a versatile framework, Machina.NET empowers engineers, designers, and programmers to seamlessly integrate robotic arms into their workflows, providing unparalleled control and coordination. By bridging the gap between digital design and physical execution, Machina.NET transforms concepts into tangible reality, enabling intricate tasks ranging from material handling to complex assembly (López, 2019).

Figure 33 introduces a pivotal moment, unveiling the Grasshopper script seamlessly integrated with Machina.NET. This combination symbolizes the vital bridge between digital design and the precise control of robotic systems.

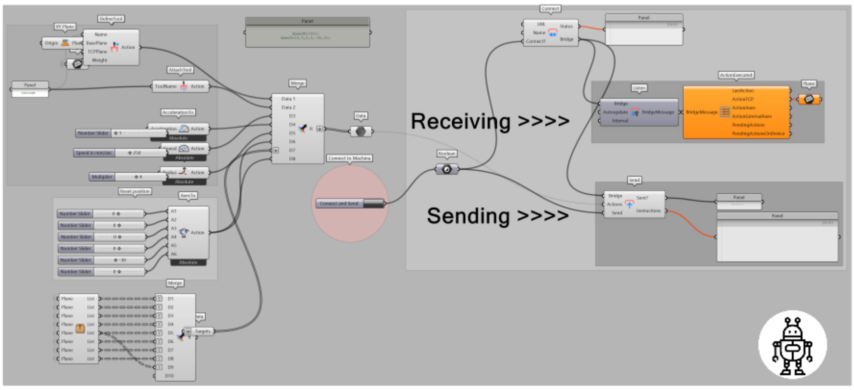

Figure 33. Grasshopper Script shows the script of Machina.NET to control the robotic arm (By author, 2023).

As the narrative progresses to Figure 34, a comprehensive visual unfolds, capturing the essence of robotic orchestration. The Machina.NET application is showcased on the left, establishing a seamless connection to the robotic arm presented in the center. Adjacent, the Grasshopper interface is revealed on the right, complete with a conspicuous 'Connect' button. This button, when activated, catalyzes to initiate the fabrication process, a journey vividly illustrated in Figure 35. Upon activation, Machina.NET comes to life, meticulously transmitting the orchestrated commands to the robotic arm, aptly encapsulating the harmonious synergy between technology, precision automation, and human intent.

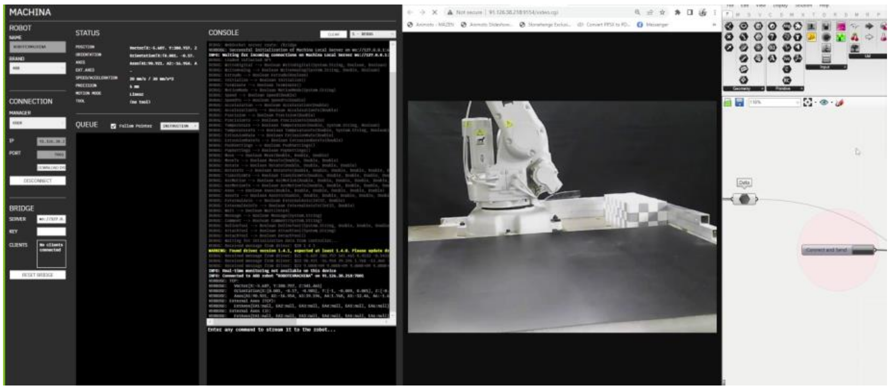

Figure 34. shows on the left Machina.NET application that control robotic arm (By author, 2023).

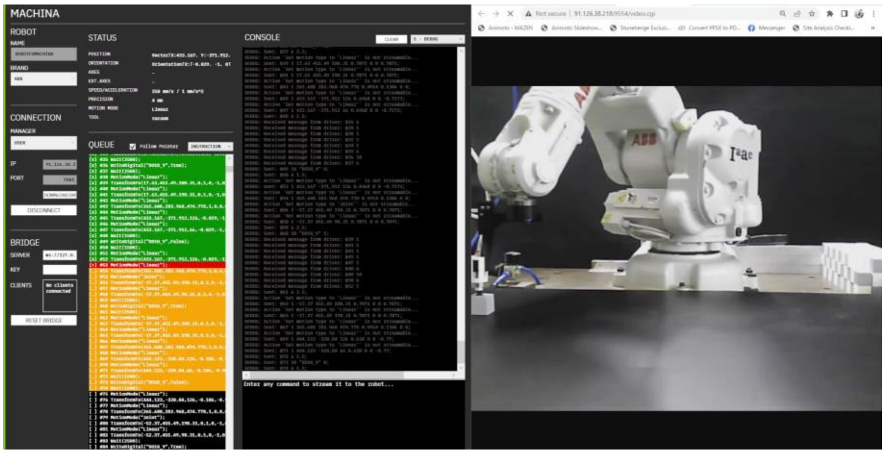

Figure 35. shows the fabrication started in Machina.NET to send the orders to the robotic arm (By author, 2023).

3. Discussion

The integration of AI, particularly exemplified by ChatGPT, catalyzes the design process by enabling meaningful interactions between human creativity and computational capabilities. The transformative power of Stable Diffusion is showcased as it translates textual prompts into vivid images, bridging the gap between linguistic expression and visual representation. Python scripting empowers designers to process and analyze complex image data, facilitating the transition from data to meaningful design parameters within Grasshopper's parametric environment. Grasshopper emerges as a pivotal platform where algorithmic design and creative exploration unfold. Through Python-generated data, intricate geometries are created, iteratively refined, and simulated for stability using PhysX.GH. This digital realm then seamlessly converges with the physical world by integrating robotic systems via the Robot Plugin, thereby unlocking the potential for robotic-assisted fabrication. The orchestrated connection between Machina.NET, the robotic arm, and Grasshopper enables a fluid translation of digital design intent into tangible structures.

The transformative workflow spans from conceptualization to physical realization. The paper highlights the potential to revolutionize architectural practices by leveraging AI's creative and analytical capabilities and the precision of robotic systems. The seamless interaction between these technologies promises enhanced efficiency, accuracy, and sustainability in architectural design and construction. However, the paper acknowledges the challenges that arise from this integration, emphasizing the need for interdisciplinary collaboration and addressing technical complexities. Overall, the discussion encapsulates the promise and challenges of this innovative approach, inspiring further exploration and research into the dynamic intersection of robotics, AI, and architecture about using different types of robotic arms and how AI will assist it with different objectives.

4. Conclusions

The Paper explored a novel and innovative approach to digital fabrication that leverages the power of artificial intelligence and robotics. It has demonstrated how the integration of ChatGPT 4 and Stable Diffusion can generate diverse and creative design ideas from textual prompts. It has also showcased how Python, Grasshopper, PhysX.GH, Robot Plugin, and Machina.NET can facilitate the design's analysis, modeling, simulation, and fabrication. The Paper has contributed to the field of digital fabrication by providing a comprehensive and detailed workflow that bridges the gap between text and reality.

It has highlighted the potential of using AI-generated design prompts to enhance human creativity and innovation. It has also emphasized the importance of ensuring the structural integrity and feasibility of the design. It has suggested ways to evaluate and compare the design results, explore the ethical and social aspects of using AI-generated design prompts, extend the workflow to other types of design domains, and improve the scalability and accessibility of the robotic fabrication process.

Acknowledgements

We extend our sincere gratitude to the Institute for Advanced Architecture of Catalonia (IAAC) for providing the essential robotic arm model and tool through their enlightening summer school workshop on robotics. This immersive experience greatly influenced the direction of our research, enabling us to explore the dynamic relationship between design and robotics. We would also like to acknowledge Engineer Omar for his invaluable assistance in reviewing and refining the Python code generated by ChatGPT4. His expertise significantly enhanced the quality and reliability of our computational processes, ensuring the seamless integration of AI-generated content into our design exploration.

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COMPUTATIONAL OPTIMIZATION OF ARCHITECTURAL SPACE PLANNING

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Abstract. Automated space layout planning has been a long-standing problem in the field of computer-aided design. The challenge lies in generating an optimal space design that has a well-defined vision and a multitude of competing objectives and evaluation measures. Computational approaches assisted designers in exploring design solutions and fulfilling some non-geometric goals more effectively and efficiently. However, quantifying spatial qualities for computational representations is challenging, especially where a multitude of interrelated objectives are needed to be met, such as wayfinding, maximizing views to outside, maximizing visibility, and minimizing travel, alongside the functional relations of the spaces with each other. Moreover, there could be a change in these intended objectives, which requires space design adaptation. Thus, there is a need for more flexible, fast, and automated design tools to be used in the design process. This paper presents a framework to generate optimal architectural space planning solutions through an interactive design system that takes geometrical, topological, and performance goals and design constraints as input. This system is based on data structure representations combined with evaluation and optimization algorithms and a parametric representation. Through a theoretical and analytical inductive study of the previous research in this field, defined steps for a computational approach for space planning optimization was proposed by presenting architect-friendly tools and graphics to simplify producing realistic optimal solutions for the required space planning problems.

COMPUTATIONAL OPTIMIZATION OF ARCHITECTURAL SPACE PLANNING

Keywords: *Computational Design, Space planning, Design Optimization, Performance-driven Design*

ملخص. التصميم الآلي لتخطيط الفراغات كانت ولا تزال مشكلة طويلة الأمد في مجال التصميم الحوسبي. يكمن التحدي في إنشاء تصميم الفراغ الأمثل الذي يحتوي على رؤية محددة جيدًا والعديد من الأهداف المتنافسة ومقاييس التقييم. ساعدت أساليب الحوسبة المصممين في استكشاف حلول التصميم وتحقيق بعض الأهداف غير الهندسية بشكل أكثر فعالية وكفاءة. ومع ذلك، فإن تحديد الصفات المكانية لتمثيلها حسابياً يعد تحدياً، بالأخص عندما يلزم تحقيق العديد من الأهداف المترابطة التي يجب تحقيقها مثل تحديد الطريق، وتعظيم الرؤية للخارج وتحسينها، وتقليل مسافة الارتحال، إلى جانب العلاقات الوظيفية للفراغات مع بعضهم البعض. علاوة على ذلك، يمكن أن يحدث تغيير في هذه الأهداف المحددة والذي يتطلب تكييف تصميم الفراغ مجدداً. لذلك، هناك احتياج إلى أدوات تصميم أكثر مرونة وسرعة وآلية لاستخدامها في عملية التصميم. تعرض هذه الورقة البحثية إطار عمل لإنشاء حلول مثلي لتخطيط الفراغ المعماري من خلال نظام يأخذ الأهداف الهندسية والطوبوغرافية وأهداف الأداء ومعوقات التصميم كمدخلات. ويستند هذا النظام إلى عمليات تمثيل هيكل البيانات بالاقتران مع خوارزميات التقييم والمثالية والتمثيل البارامتري. ومن خلال دراسة نظرية وتحليلية استقرائية للأبحاث السابقة في هذا المجال، اقتُرح خطوات عمل محددة لنهج حوسبي لتحسين تخطيط الفراغ من خلال عرض أدوات ملائمة في الاستخدام للمهندسين المعماريين لتبسيط التوصل إلى حلول مثلى واقعية لمشاكل تخطيط الفراغ المرجوة.

الكلمات المفتاحية: *التصميم الحوسبي، تخطيط الفراغات، تحسين التصميم، تصميم قائم على الأداء*

1. Introduction

Architectural designers need to address multiple requirements imposed by clients and regulations when designing space layout planning, however, the limitations of time and resources can restrict designers from exploring novel design solutions (Mukkavaara & Sandberg, 2020). A way to address these challenges is with computational design which is a shift in thinking that relies on the power of computation and computational thinking (Boissieu, 2022; Mikaelsson, 2022; Mukkavaara, 2021; Ma et al, 2021). This section will represent the most recent terminologies and classifications for architectural computational design to introduce a well-defined knowledge of this field.

1.1 COMPUTATIONAL DESIGN

Since the computational revolution in academia in the 1950s, Computational design or computer-aided design (CAD) software has had a paradigm shift impact on architectural practice. (See Figure 1). The first computer tools to be widely adopted by architectural designers were computerized versions of traditional drafting and rendering tools. While they allowed designers to represent their content much faster than with traditional methods, they did not fundamentally engage in the process of design.

The term computational design (CD) rapidly developed and has been treated as an umbrella for multiple overlapping design approaches. (See Figure 2). (Radford & Gero, 1988). (CD) approaches aim to use computers not only as an electronic drawing board but also to generate and assist, or even fully automate, the designers' work, effectively and efficiently enhancing the design exploration process.

During the last decades, approaches of the CD have emerged, and design professionals and researchers have adopted different terminologies and classifications to address these approaches. (Caetano et al., 2020).

Figures 3 and 4 represent two other classifications that differ from Radford and Gero's. These classifications include the recent research terminologies and approaches that will be discussed in this paper for a better understanding to the CD.

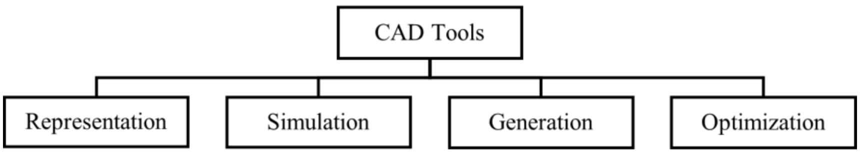

Figure 1. CAD Tools (Radford & Gero, 1988)

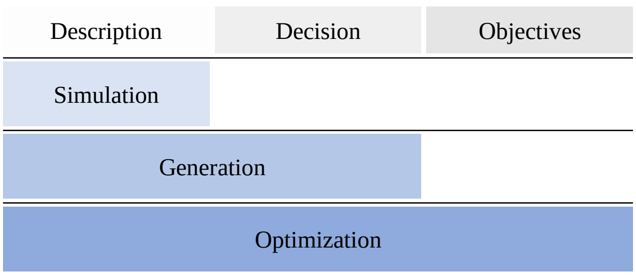

Figure 2. Classification of CAD models according to the location of description, decision, and objectives (Radford & Gero, 1988)

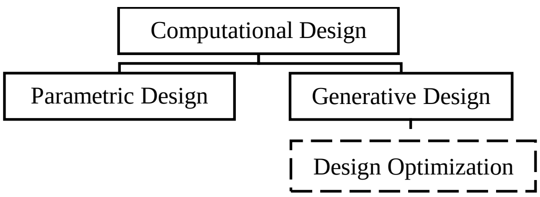

Figure 3. Relationships between computational design and subfields (Mukkavaara, 2021)

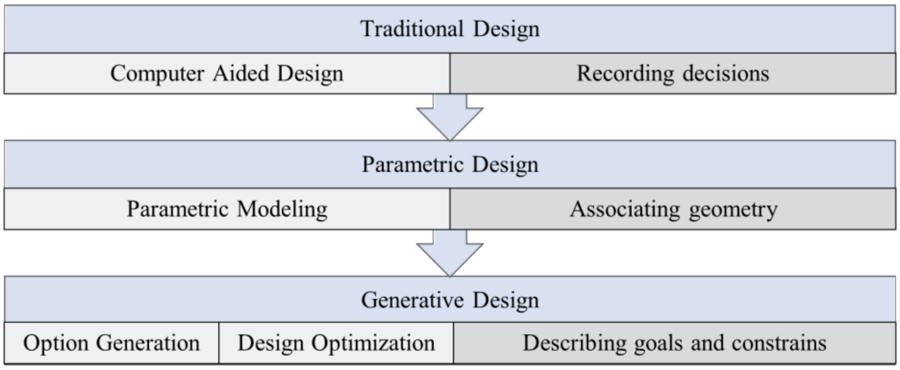

Figure 4. The dissociation of GD summary by Süße (Süße & Putz, 2021)

1.2 PARAMETRIC DESIGN

Parametric design is one of the most common subfields of computational design (Caetano et al., 2020). It is fundamentally developing the way designers use computers to refine their work. Parametric software tools allow the designer to not only define a final geometric solution but also adjust specific parameters, or values, that drive different versions of the design.

This can be done by exposing the critical parameters that drive different variations and automatically generating different versions by readjusting those parameters. Instead of rebuilding the model from scratch each time, the design can be easily adapted to changing conditions. Parameters can be changed manually by a user or automatically using a developed mechanism.

Most importantly, as a result, design alternatives can be generated within a parametric model by directly embedding the design constraints and goals of the problem rather than drafting the geometry of a single design solution. (Mukkavaara, 2021; Boissieu, 2022; Mikaelsson, 2022).

1.3 GENERATIVE DESIGN

While the parametric approach has pushed the possibilities of human-computer interaction in the design process, for the most part, the human designer must investigate different design options by manually varying individual parameters and evaluating each option using their criteria and intuition in the same traditional way. (Nagy et al., 2017).

Generative Design (GD) is another subfield of computational design that concerns this limitation by tasking a computer with exploring the design space and then providing rapid feedback to the designer on which alternative is considered promising for further analysis. This approach works by feeding the computer with logical inputs instead of geometry or raw parameters, as well as coupling the system with evaluation and analysis algorithms for specific predetermined criteria. (Mukkavaara, 2021)

As a result, the computer can process data much quicker than a human, allowing a wider range of exploration of novel design solutions that would otherwise be hidden from the human designer. However, the emphasis of generative design approaches is on the exploration of the design solutions; this shouldn't be taken as a final product but, moreover, as a baseline for the design development that requires further analysis by the human designer. (Nagy et al., 2017; Mukkavaara, 2021).

1.4 DESIGN OPTIMIZATION

The role of computational design optimization has been highlighted by Radford and Gero (1988), even before the prevalence of the application of computational design optimization to architecture. (Radford and Gero, 1988).

Design Optimization uses a specific category of evolutionary optimization algorithms to support the optimization of design solutions. Optimization is accordingly defined as the process of finding the minimum or maximum value of a function that depends on a set of parameters and is subject to a set of constraints. (Mukkavaara, 2021).

Therefore, to explore the possibilities of generative design, the parametric model needs to be extended through two main phases:

1. In the first phase, specific evaluation criteria and metrics must be included by which each design option can be generated and evaluated to determine which designs perform better than others.
2. Secondly, an evolutionary optimization algorithm is needed to be connected with the system that can adjust the input parameters of the alternatives, get back a report from the metrics, and develop the parameters to find high-performing designs while also exploring the full possibilities of the design space using principles of evolution to create sequential generations of iterated design trials and evolve them to reach the optimum solution. (Nagy et al., 2017; Mukkavaara, 2021).

This paper suggests a framework for generative design through inductive approach of analyzing some case studies specifically geared towards architectural space planning, to provide non-programming-familiar architectural designers with an understanding of the workflow of optimizing space planning through the generative design process as Ma et al. states that there is a lack of previous knowledge and resources regarding GD programming and development. (Ma et al, 2021)

Hence, this paper structure was arranged to include an introduction of the computational design dissociation (section 1), an overview of some previous related works that conduct different computational implementations to achieve the optimization of generation design for space planning in architecture (Section 2), following by an analysis of a framework based on analyzing some of these case studies to induct their generative design system methods through the framework (Section 3), leading to a discussion to summarize the findings of the previous section for a suggested framework, methods, and guidelines for optimizing space planning using generative design, ending up with the conclusion and further work recommendation (Section 4).

2. Related work

The application of generative design by multi-objective optimization towards solving complex design problems is well known in the field of engineering. In 2015, Calixto tried to organize, classify, and discuss about twenty-two years of space planning based on an evolutionary approach to orient future research in the field. Calixto compared and classified the evolutionary system used, the space planning system, the algorithm representation of the evolutionary system, and the type of plan layout problem solved. Yet, he concluded that improving the new methods and the old ones is necessary for the development of this field. (Calixto & Celani, 2015).

Thus, there are many previous studies on the optimization of space planning problems. This section will present some selected works that tried to implement these studies into an actual space design that responded to the values and intentions of a designer's subjectivity.

In 2017, Nagy et al. described a generative design workflow applied to architectural indoor space planning of an office space. They used a generative system called Voronoi diagrams to produce their structure order, also, six performance metrics (adjacency preference, work style preference, buzz, productivity, daylight, and views to outside) were subjected to a multi-objective genetic algorithm to generate design alternatives. Although their findings were encouraging, they stated that their methods needed to be more flexible so that additional parameters could be exposed and controlled by multi-objective genetic algorithms. They also highlighted that the output from a generative design workflow should not be thought of as final but rather as a baseline for further analysis and development to finalize the design. (Nagy et al., 2017).

Zhouzhou (Zhouzhou Su, 2015) described a workflow for optimization-based design to architectural form-finding applied to a nursing unit where two objectives (minimizing nurses' travel distance and maximizing patient room's daylight) were subjected to a multi-objective optimization algorithm to optimize generating design solutions. Zhouzhou used a developed framework that depends on offline parallel simulation to reduce the time of computing using the divide and conquer (D&C) technique, which works by dividing a large problem into manageable sub-problems and combines solutions in the final solution. The Author was motivated by the need to create tools that are quick to build and fast to run, and support architects, and could quickly find an optimal design applicable for architectural use through applying his suggested method. Galapagos, Diva, and Rhino/grasshopper were the VPLs used for this study. However, Zhouzhou mentioned that his study cannot simply be generalized to other design problems because it was limited to his specific design problem.

Intending to optimize a basic model of a project in the aspects relevant to early project development, Rohrmann (Rohrmann, 2019) applied a generative design framework to a specific type of Siemens Real Estate office building where seven variables and eight objectives were identified to test the approach of developing variables, constraints, and metrics to evaluate design options and determined the optimized one with the assessment of the genetic algorithm Nondominated Sorting II (NSGA-II) over several generations.

Following Aupys' work, a case study of Generative design for Hospital Pharmacy to optimize spaces and flows was conducted to integrate algorithms and coding into architecture and engineer workflows. In this case study, Firstly, Aupy defined the design goals that were oriented by the hospital's needs, which were: Minimize stock space, maximize workplace, reduce flow paths, and optimize natural light in the workplace. Then, Aupy applied the generative design process using Revit, Dynamo, and Refinery by writing scripts and analyzing the solutions. (Aupy & Mannarella, 2019).

The work of Das et al. sought to generate an inpatient tower at a general hospital through a generative design system and against well-defined criteria. They take advantage of efficient tree representation via Kd-trees as an initial generation method. Furthermore, they implement spatial grouping and circulation functions to achieve more feasible architectural floor planning results for their case study. Their system is developed as a library that can be loaded into Dynamo VPL, allowing users to generate and evaluate various floor plan representations. However, they mentioned that their system generates design options without learning from its previous iterations, sometimes leading to architecturally inadequate proposals, and suggested coupling their system with an optimization genetic algorithm in future work. (Das et al., 2016).

Keshavarzi and Rahmani-Asl developed an interactive design system that takes geometrical, topological, and performance goals and constraints as input and provides optimized spatial design solutions as output. They proposed permutation methods for existing space layout graph representations, namely O-Tree and B-Tree representations, implementing their proposed floor planning methods as a package for Dynamo, a visual programming language

(VPL) tool. They illustrated their results through two sets of case-study experiments for residential floor planning tasks by (a) measuring the ability of the proposed system to find a known optimal solution and (b) observing how the system can generate diverse floor plans while addressing a constant residential design problem. Their results offered a diverse set of solutions for a residential floorplan corresponding to the local optimums of the solution. (Keshavarzi & Rahmani-Asl, 2021).

Thus, the following section analyzes a framework that has been inducted out of these studies and shows how they can be used to automate a space planning optimization process, ultimately guiding optimal design solutions.

3. Space planning optimization

Space planning in architecture (SP) is a field of research in which the process of arranging a set of space elements and problems such as distance, adjacency, and other functions of arrangement is a principal concern to solve the organization of the space to attend to a specific purpose. Optimization of SP problems has been developed since the 1960s but is not yet fully explored. Therefore, Space planning optimization problems form a wide field of research and have been explored since the beginning of the development of the computational design field. (Calixto & Celani, 2015).

According to a literature review study on computational SP approaches for the last 22 years, the method that was employed in nearly all floor planning and space layout systems was a combination of a generative mechanism for the creation of alternative variations to generate plan alternatives in space planning problems and an evaluation mechanism to assess these variations to point out the most optimal ones. (Calixto & Celani, 2015; Keshavarzi & Rahmani-Asl, 2021).

In this section, the most recent case studies of space planning optimization will be discussed including their generation methods, evaluation mechanisms, and software used in a way to simplify a user-friendly framework that relies mostly on graphical user interfaces (GUI) rather than coding scripts.

3.1 THE SPACE PLANNING OPTIMIZATION FRAMEWORK

It’s concluded from the previous studies that any generative design framework shares basically: (Mahmoud et al., 2019)

a. Architectural programming and topological diagrams provide topological relations between spaces without any geometric solutions.
b. Generating design alternatives realizes all design constraints.
c. Evaluation of design solutions analyzes their efficiency.

These could be utilized in a framework of five main steps leading to an optimization product. These five steps are: (See Figure 5) (Nagy et al., 2017; Aupy & Mannarella, 2019; Rohrmann, 2019; Mukkavaara, 2021)

1. Define
2. Generate
3. Analyze & Evaluate
4. Evolve & Optimize
5. Explore & Select

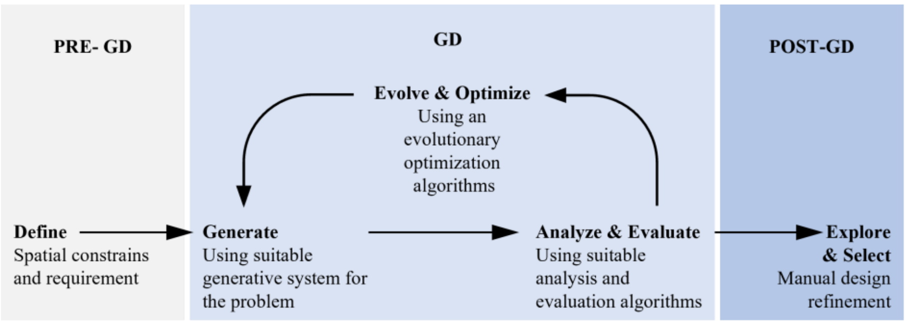

Figure 1. General Generative Design for Architecture workflow inspired by (Nagy et al., 2017); Aupy & Mannarella, 2019; Rohrmann, 2019; Mukkavaara, 2021)

The following section is representing an analysis of every step in the light of some selected case studies to show the recent usable systems and techniques.

3.1.1 Define

The first step is to determine the design problem definition that needs to be generated and/or optimized. This definition includes:

- Special requirements (list of spaces, their sizes, and adjacencies between them),
- Site boundaries,
- Design constraints and variables,
- Design metrics and measures.

This definition could be in the form of a parametric model or direct inputs of a CSV file or custom node on VPL software (Figure 6).

Figure 6. Various types of (Define) nodes in the GenFloor library for generating the Spatial Requirement data (Keshavarzi & Rahmani-Asl, 2021)

3.1.2 Generate

To start generating the space plan from the previous step of defining the inputs, the user needs to decide which creation method is most suitable for the problem and by which tool.

Many generation methods have been developed and tested for different design problems such as Half plan, K3d tree, Shape Grammars, Blocking, One-to-one assignment, and Slice tree structure. However, Space data tree methods have shown as very promising creation methods for space planning and have been used and developed to user-friendly nodes and packages for many VPL interfaces for its multiple benefits. (Keshavarzi & Rahmani-Asl, 2021; Das et al., 2016). These benefits are representing in provides fast and efficient data storage to represent spatial data, also, can randomly ascertain circulation paths between any two spatial locations in the space plan, aiding in space plan appraisal through key metrics such as nurse travel routes and distances, patient flow paths, fire egress routes, etc., in a healthcare facility as it was shown at the general hospital space layout generation developed by (Das et al., 2016).

Here's a description of the two space data tree methods used in the case studies mentioned above.

K-d tree

A k-dimensional tree (K-D) is a method of binary search and partitioning trees in which a set of points is represented in a multi-dimensional space (Knecht, 2010). A dimensional space is divided by partition planes that are perpendicular to one of the coordinate axes. These planes are formed by taking the median or average of the coordinates of the points. (Calixto & Celani, 2015).

This method was used to develop a package to generate a space layout for a general hospital by Das (Das et al., 2016) (as shown in Figure 7) called “Space plan generator” to assign departments to the site based on user’s preference values while simultaneously building the space data tree.

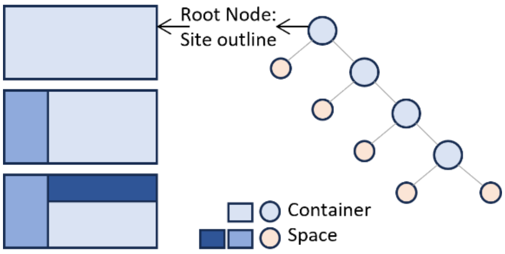

Figure 7. Space Data Tree construction based on K-d data structure binary tree. (Das et al., 2016)

Non-Slice Tree Structure

Such representation is often defined in constraint graphs defining the horizontal and vertical relations among the modules. While no bisection of a specific boundary is performed, non-slicing representations can be bounded by a given fixed outline. Representations such as Sequence Pair, Bounding Slicing Grid, B*Tree, Integer Coding, O*Tree, Corner Block List, and Transitive Closure Graph are among the widely used non-slicing methodologies.

(Keshavarzi & Rahmani-Asl, 2021) have developed a user-friendly package to generate layout space planning taking advantage of non-slicing O*Tree and B*Tree representations (See Figure 8) called “Gen-floor”.

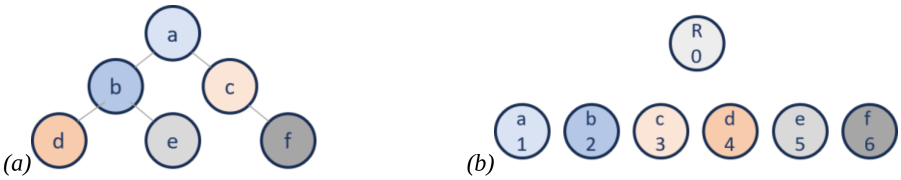

Figure 8. Standard Tree of a (a) binary tree for B*Tree and (b) nonbinary tree for O-Tree. n = 6 and each node corresponds to a spatial input entity (a-f). (Keshavarzi & Rahmani-Asl, 2021)

3.1.3 Analyze & Evaluate

To complete the generation process of the space plan, the resulting floor plan needs to be then analyzed and guided by various customized fitness functions that represent the qualitative design goals corresponding to the project requirements and focuses on the process that follows space layout generation: the analysis and evaluation of the generated design options. Many evaluation methods have been developed over the years, each for a specific needed target. For space planning, methods like Quadratic Assignment Problem, Interactive Evaluation, Adjacency Matrix, and Graph Theory were commonly used. (Calixto & Celani, 2015).

As samples for the intended evaluation fitness or measures, at the Toronto office case study conducted by Nagy et al., Adjacency preference (the travel distance from each employee to their preferred neighbors and amenities), Work style preference (the suitability of an assigned neighborhood's daylight and distraction measurements), Buzz (the amount and distribution of high-activity zones), Productivity (concentration levels at individual desks based on sight lines to other desks and other noise sources), Daylight (the total amount of natural daylight entering the space throughout the year), and finally, Views to outside (the ratio of workspaces with an unobstructed view to the exterior glass façade) were the main measures that guided the final space planning to reach its optimum solution. (Nagy et al., 2017)

Also, in the case study of a new hospital bed tower building conducted by Das et al., the study metrics were maximizing patient beds per floor, minimizing nurse travel distance, and minimizing view impedance from the existing bed tower. (Das et al., 2016)

Therefore, to analyze the generated data structure of the previous "generate" step to meet the targeted metrics, many analyzing, and searching algorithms have been developed and used either by scripting codes or in a form of a user-friendly graphical interface.

Space analysis is an example of a VPL add-on for Pathfinding, Visibility, and Acoustics Analyses developed by Goldstein (Goldstein et al., 2020).

For pathfinding, Goldstein developed the Paths by applying Dijkstra's algorithm to a space lattice grid. To take advantage of Dijkstra's algorithm, the node precomputes all paths to or from a single point.

To achieve the visibility goal of maximizing compelling views, minimizing visual distraction, and ensuring certain elements can be seen from certain locations, the system uses a grid-based approach that repurposes the implementation of Dijkstra's algorithm developed for pathfinding. Thus, the visibility from the viewpoint to any other point is approximated as the fraction of shortest paths that are not cut off by barriers.

For noise and privacy considerations, the system's method to simulate acoustics was the Transmission-Line Matrix (TLM), a simple algorithm that propagates impulses on a grid.

Many other systems were developed for different design metrics in the previously mentioned case studies, using specific algorithms for each goal.

3.1.4 Evolve & Optimize

The exploration of design options and their trade-offs to reach optimal solutions is the next step in a generative design workflow. The optimization concept entails combining the generator system or method with optimization

Genetic Algorithm (GA) to improve design candidates by learning from each iteration to reach optimal floor layouts, as driven by project goals.

GA is an approach driven by a set of biologically inspired processes (for example, mutation, crossover, and selection), in which each solution is evaluated by a fitness function (a function that numerically depicts the performance of a solution based on the objectives of a given problem). The biologically inspired processes are used, in each iteration of a genetic algorithm approach, to generate a solution set (called a 'population') that increasingly improves the fitness of its solutions with each iteration. Given the focus of genetic algorithms on minimizing or maximizing different objectives (for example, minimizing travel distance), it has been shown to have the potential for design problems with distinct and measurable objectives. (Mukkavaara & Sandberg, 2020)

In addition, GAs are used to solve multi-objective optimization (MOO) problems (optimization that is intended to find minimum or maximum values of multiple objective functions). MOO is a particularly interesting tool for building design because of the frequent need to address multiple and competitive objectives. Therefore, numerous studies have combined their generative methods with various genetic algorithms; here's a glimpse at two of the most used methods for space planning optimization, as well as their graphical interface tools:

Refinery

Refinery is a plug-in for Dynamo that optimizes using **Nondominated Sorting Genetic Algorithm II (NSGA-II)** (a computationally fast and elitist GA to evaluate performance) for its optimization. It runs locally and is controlled by its graphical user interface (GUI). It docks onto the graph, generates new sets of input values, and registers the corresponding outputs. It finds out which values result in high-performing solutions and optimizes the designs in that direction via crossover and mutation. This could be done by assigning the fitness of minimization and maximization to the system. It has been used by (Keshavarzi & Rahmani-Asl, 2021; Aupy & Mannarella, 2019; Nagy et al., 2017; Goldstein et al., 2020; Rohrmann, 2019).

Galapagos

Galapagos is an evolutionary solver with **an embedded genetic algorithm framework** that uses feedback loops in the initial stage to reconsider the design variables. In each consecutive analysis, the algorithm is trained by the results to find a better solution. This optimization engine was used by Mukkavaara and, Lu. (Mukkavaara & Sandberg, 2020; Mukkavaara, 2021; Lu et al., 2022)

3.1.5 Explore & Select

The overall optimal design will not necessarily be found through the search process. Therefore, once a set of design alternatives is selected, they can be further analyzed by the human designer and developed into a final design. It is important to note that since the multi-objective genetic algorithm (MOGA) follows a stochastic process based on sampling a limited number of designs from the design space, Furthermore, not all aspects that are important to an architectural design can necessarily be represented as a metric in the generative design model. Some aspects, such as beauty, cannot be quantified, and thus need to be considered once the generative design process is complete. (Nagy et al., 2017).

4. Discussion and Conclusion

This section discusses and concludes the suggested design framework, analyzed previously in section 3 of this paper, utilizing generative design exploration tools for optimizing space planning, which consists of the inducted five main steps, that are used previously in generative design frameworks with their commonly used tools from different VPL environments with the focus not on a specific environment but rather on the process itself. (See Table 1).

It has been concluded from Table 1 that a well-defined problem, with a suitable data structure generation system, coupled with evaluation algorithms for the required analysis of the problem, also, a genetic optimization algorithm attached to the whole process, could perform a novel set of optimum solutions that could be explored by the human designer and give him access to numerous well-performing options. This process could be familiar and used by more architects with more architect-friendly developed interfaces and tools, as discussed in this paper.

As a conclusion, Generative design for architecture is a computational approach to design that allows designers to discover and investigate unexpected novel designs, navigate trade-offs between high-performing designs, determine and negotiate constraints and goals rather than form, and co-design between humans and computers. However, the solutions that generative design methods produce are not the “answer” but rather the guide towards a set of potential manipulations that could be taken into consideration in addition to all the other architectural, structural, aesthetical, and environmental aspects.

Automating the space planning optimization process has been negotiated many years ago but is still not fully familiar to all architectural users because of its interdisciplinarity and interpretation with other scripting and coding fields that make it harder for architects to engage the automation process at the design loop. However, this paper represented a framework that was developed from many trials conducted in recent works. This framework simplified the generative design optimization process to make it easier for non-programming-familiar users to start discovering this very promising design method.

For further work, the suggested framework of this paper was inducted from previous works and needs to be tested on a case study to be verified, also, more research is needed to investigate this design approach alongside the help of programmers to introduce more architect friendly GUI and tools to develop the process with a full package of all other aspects. This could introduce new ways to think, make, and produce architecture while unlocking the creative power of the computational optimization process for designers and engineers.

TABLE 1. Space planning generative design optimization framework

PHASE	STEP	TOOL
Pre GD Represents the collecting data of the design metrics	1. **Define**	Human Designer & stakeholders
	Project Data Site boundary Constrains Variables Main Zones Spaces Adjacency	
GD The generative design process itself	2. **Generate**	Data Structure System
	Where the system generates the Spatial Blocks based on the selected data structure by the designer that suits mostly the spatial problem, which was conducted from analyzing previous studies that space data tree systems are commonly used and utilized as user-friendly tools in many case studies	**K-d** for departments and sub-zones **Ex:** SPG **Non-slicing tree structure** when no bisection of a specific boundary is performed **Ex:** Gen-floor
	3. **Analyze & Evaluate**	Evaluation algorithms
	Where the predetermined performance metrics which will be used to measure the performance of a single design solution are calculated and input to the ongoing search algorithm to be evolved and optimized for the exploration of the space plan design through a MOGA	**Dijkstra's algorithm** for Pathfinding **A grid-based approach of Dijkstra's algorithm** for visibility goals **(TLM)** for Acoustics **Ex:** Space analysis add-on for Dynamo
	4. **Evolve & Optimize**	NSGA-II
	Through using the most suitable Genetic algorithm for the specific design problem requirements Many researchers had developed tools for the non-programming familiar users to deal with the algorithms in a more graphical interface	**Ex: Refinery** a plug-in for Dynamo An Embedded GA Framework **Ex: Galapagos** a plug-in for Grasshopper
Post GD To determine the optimal design solution	5. **Select & Explore**	**Human Designer** still has to make the decisions but does so with access to numerous relatively well-performing generated options.
	Where the investigation of the resulting analysis is held against the predetermined targeted criterion	

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A SYSTEMATIC REVIEW OF ROBOTIC 3D CONCRETE PRINTING

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Abstract. This systematic review examines the patterns, themes, and trends in the field of robotic 3D concrete printing. The methodology entails a comprehensive search and screening of relevant literature from databases Scopus and Cumincad. Through a stringent screening process based on specific inclusion criteria, resulting in a final dataset of research papers. The results are analyzed by network visualization techniques and keyword co-occurrence analysis with the data visualization tool VOSviewer. The network visualization enables insights into the literature structure and identifies research themes and emerging trends. The results emphasize integrating technological developments, optimizing the printing process, investigating concrete materials and their performance, and focusing on sustainability in 3D concrete printing. This review contributes to the comprehension of the current status and advances in robotic 3D concrete printing.

Keywords: *robotic fabrication, concrete printing, additive manufacturing.*

ملخص. تتناول هذه المراجعة المنهجية الأنماط والموضوعات والاتجاهات في مجال الطباعة الخرسانية ثلاثية الأبعاد الروبوتية. وتنطوي المنهجية على بحث شامل وفحص الأدبيات ذات الصلة من قواعد البيانات Scopus وCumincad. من خلال عملية فحص صارمة تعتمد على معايير إدراج محددة، مما يؤدي إلى مجموعة بيانات نهائية من الأوراق البحثية. يتم تحليل النتائج من خلال تقنيات تصور الشبكة وتحليل التكرار المشترك للكلمات الرئيسية باستخدام أداة تصور البيانات VOSviewer. يتيح تصور الشبكة إلقاء نظرة ثاقبة على بنية الأدبيات ويحدد موضوعات البحث والاتجاهات الناشئة. تؤكد النتائج على تكامل التطورات التكنولوجية، وتحسين عملية الطباعة، ودراسة المواد الخرسانية وأدائها، والتركيز على الاستدامة في الطباعة الخرسانية ثلاثية الأبعاد. تساهم هذه المراجعة في فهم الوضع الحالي والتقدم في الطباعة الخرسانية ثلاثية الأبعاد الروبوتية.

الكلمات المفتاحية: *التصنيع باستخدام الروبوت، الطباعة ثلاثية الأبعاد للخرسانة، التصنيع الرقمي بالإضافة.*

1. Introduction

Architectural design and production have consistently evolved and improved over time by adapting to the latest technology developed in response to the needs and opportunities of the time. With the ongoing development of mass production and robotic technologies, it is anticipated that architectural design and production will also adapt to these changes. The emergence of the "file-to-factory" process with the advancements in the technology, design, and fabrication phases are directly connected and controlled. The process obtains the physical fabrication by using the data generated from design and performance analyses in the computer environment. The elimination of the need for intermediaries by the opportunity to comply with the design and fabrication, designers can directly produce the design products by design files. In recent years, investments in digital fabrication in the building industry and academic literature have been significantly on the increase due to the precise and fast production capability of robots.

This innovative construction approach involves the advantage of robots' abilities to interact with materials and conduct accurate building operations. One of the focus areas in digital fabrication is robotic 3D concrete printing which involves the use of additive manufacturing methods and cement-based materials to achieve production through robotic interaction. The research area includes holistic manufacturing processes that anticipate complete 3D-printed structures to partial fabrication techniques, material, structural and geometrical performances (Carneau et al. 2020; Xiao et al. 2020). Explorations in literature push to discover the full potential of this technology, going beyond the limits of what is possible in structure and design with this new construction method. Hence, in addition to improvements in the building industry with fast and precise production, various researchers concentrated on robotic 3D concrete printing primarily exploring holistic or partial production methods (Anton et al. 2021; Xu et al. 2022). In doing so, they pave the way for creative solutions that address the changing needs of the current construction environment, alongside its increasing emphasis on sustainability, efficiency, and architectural diversity.

A systematic literature review on 3D concrete printing is essential to provide a comprehensive overview of the current state of research and development in this emerging field. This literature review contributes to the advancement and effective utilization of 3D concrete printing in construction and related industries by helping to identify knowledge gaps, and guiding future research paths. Therefore, this paper aims to provide a comprehensive analysis of the literature on 3D concrete printing by examining patterns, key themes, trends, and changes to map the relations and developments in the research field. The bibliometric data compilation was conducted through Elsevier Scopus and Cumincad online databases. The scrutinized data is synthesized within two main clusters; publication, which contains definitive information about the publications, and research info such as tool and material details, aim and method, and so on. The expected result of this research is a complementary map to identify and evaluate the most influential and ineffectual topics in the field and generate a tool for critical reading of the literature.

2. Methodology

To ensure a thorough and objective examination of the current status of 3D concrete printing, the methodology of this systematic literature review consists of three essential parts: a search and selection of relevant literature, the extraction and analysis of data, and the use of VOSviewer to visualize networks.

2.1. DATA SEARCH, SELECTION AND COLLECTION

The initial step of this research involved a comprehensive survey of the relevant academic literature in the field of 3D concrete printing. Scopus and Cumincad were selected as the databases for this research as they provide comprehensive coverage of peer-reviewed articles and conference proceedings related to construction technology and additive manufacturing. Similar keywords and subject-specific terms and limits were set for each database to make the search suitable for the research objectives. In addition, the review was limited to studies published in English in 2023 and before.

In the systematic literature search, we collected relevant research articles and conference proceedings on 3D concrete printing from the Scopus database. Specific search terms were used and appropriate limitations were applied to ensure a comprehensive and targeted search. The keywords "concrete*," "3D," and "print*" were combined to retrieve articles related to 3D concrete printing for the Scopus database. It was essential to include the asterisk (*), which served as a wildcard to allow for terms with derivative meanings like "print," "printed," and "printer" (Grames et al. 2019). To narrow the results to academic articles and conference proceedings, the search is restricted to include publication types. The focus on academic literature and conference contributions aims to bring together rigorous and up-to-date research findings in the field. As the scope of this review was limited to 3D concrete printing in construction and engineering, we excluded topics that were not relevant to the field. Other topics not related to the construction industry, such as neuroscience, medicine, and biology, were excluded from the search to ensure the retrieval of highly relevant research papers. The final dataset obtained as a result of the search includes 1583 research papers.

In addition to the Scopus database, the Cumincad database, which focuses on computer-aided architectural design research, was also included in the literature search. The database extension made it possible to collect a wider range of research publications, especially those focusing on architectural applications of 3D concrete printing. The data collection in Cumincad was conducted using the keywords "3D print" to identify articles related to 3D concrete printing in architecture and design. It was also ensured that article abstracts included the term "concrete*" to maintain relevance to the research focus. The data set obtained as a result of the research conducted in the Cumincad database consists of 91 research publications.

2.2. DATA SCREENING AND INCLUSION CRITERIA

After searching both databases, the collected articles were combined and underwent a rigorous screening process to ensure that they met the research objectives and inclusion criteria. Duplicate articles were deleted during the screening process, and the title, abstract, and keywords of each article were thoroughly reviewed to determine their relevancy. For inclusion in the literature review, papers had to meet these criteria; address issues related to 3D concrete printing, and fall within the field of construction, engineering, or architectural design. Irrelevant studies which do not meet the criteria are excluded from the literature review.

3. Results

VOSviewer software was used to have a better grasp of the linkages and correlations between the discovered keywords in the literature. To visualize and analyze the relationships between keywords in 3D concrete printing literature VOSviewer is a robust and versatile bibliometric analysis tool used in this systematic literature review. For the collocation analysis of keywords appearing in the literature VOSviewer visualization, a bibliometric analysis tool was used. The final dataset includes 1633 research papers obtained after the extraction process from the sources taken from Scopus and Cumincad databases was extracted as a RIS file and used to perform a keyword co-occurrence analysis with the VOSviewer LinLog/modularity normalization method. The minimum number of occurrences of a keyword was set to 8 and a thesaurus file was used to clean keywords that are irrelevant to the scope of the research and to merge keywords that repeat (such as 3-D, 3D, and three-dimensional). Out of the 9241 keywords, 82 of them reached the specified limitation threshold, resulting in 3 different cluster groups These components were identified based on a combination of VOSviewer's automatic clustering algorithms and manual analysis to ensure the semantic consistency and relevance of the keywords in each cluster. Each keyword is represented as a node in a network visualization made using the data provided to the program, and links between nodes are established based on how frequently they occur together in the literature that has been gathered (Figure 1). The resulting network visualization and clustered representation make the general structure of the literature easier to read and identify significant research themes, arising trends, and areas of research interest.

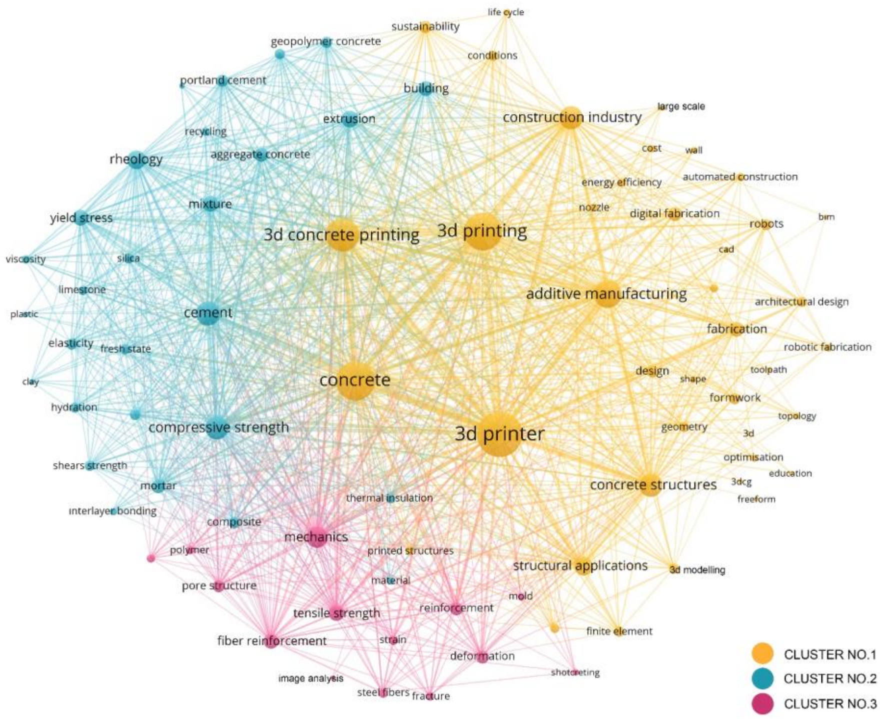

Figure 1. Keyword co-occurrence analysis network visualization and clusters.

An overlay visualization of keyword co-occurrence analysis reveals recent research trends (Figure 2) through color codes. The yellow color intensity towards the left-hand side of the network map indicates that research conducted after 2021 remains relevant with a focus on material content. It is also apparent that research with the keywords "sustainability" and "large scale" has become a growing theme after 2021. On the other hand, the purple nodes indicate that studies conducted in 2020 and before were mostly focused on understanding 3D robotic concrete printing techniques.

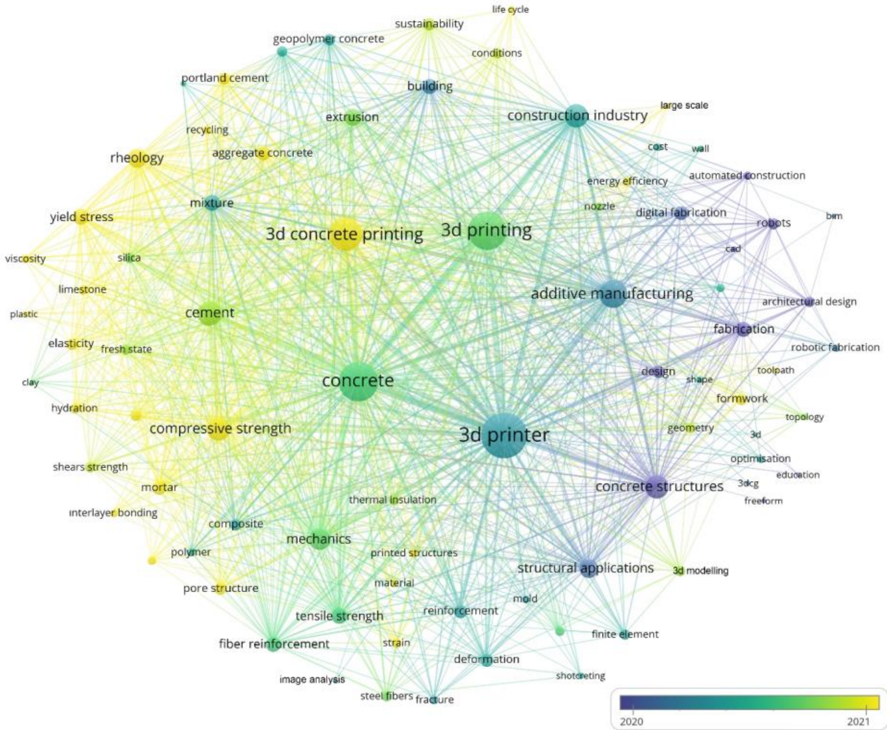

Figure 2. Keyword co-occurrence analysis overlay visualization.

3.1. CLUSTER 1: TECHNICAL ASPECTS AND SUSTAINABILITY

The first cluster is the largest keyword network created by VOSviewer by aggregating various fields (see Table 1). The inclusion of “3D printers”, “3D printing” and “additive manufacturing” in this cluster points to the technology supporting 3D concrete printing. The numerous processes and procedures needed to construct concrete structures layer by layer are represented by these keywords, which are intimately related to one another. As it offers new approaches to building design and implementation, this technology is particularly important in the context of the construction industry and structural applications.

TABLE 1. Cluster 1 keyword list ordered by occurrence counts.

Cluster	Keyword	Links Count	Total Link Strength	Occurrences
1	3D printer	81	6930	1124
	3D printing	81	4825	797
	additive manufacturing	81	2725	439
	concrete	81	5523	852
	3D concrete printing	80	3862	607
	concrete structures	80	1968	305
	construction industry	80	2204	314
	structural applications	80	1343	189
	design	73	560	85
	fabrication	73	854	124
	digital fabrication	72	686	105
	3D modelling	67	407	62
	conditions	66	438	60
	formwork	66	472	77
	geometry	63	443	65
	nozzle	62	273	41
	sustainability	62	561	82
	architectural design	61	389	62
	printed structures	61	278	39
	finite element	58	373	65
	optimisation	58	220	34
	quality control	56	250	38
	robots	55	527	77
	numerical modelling	54	312	51
	wall	50	160	24
	cost	49	189	31
	energy efficiency	49	255	39
	large scale	48	162	20
	automated construction	47	281	44
	life cycle	46	177	27
	topology	41	182	29
	robotic fabrication	39	201	33
	shape	38	160	24
	3D	36	70	10
	freeform	35	72	10
	CAD	33	98	18
	toolpath	30	89	12
	3DCG	27	57	12
	BIM	22	53	10
	education	22	66	14

The keywords in this cluster reflect the essence of 3D concrete printing research, as defined by keywords linked to technical elements and sustainability. The strong links between keywords such as "3D printer", "additive manufacturing", and "sustainability" in this cluster indicate that they often appear together in research papers, suggesting that studies examining 3D printers often encompass discussions on sustainable material design, and construction practices (Arunothayan et al. 2022; Bhattacherjee et al. 2021). The co-occurrence of "concrete" and "3D concrete printing"

emphasizes the significance of the printing material itself which leads to the interpretation of the research in this cluster focusing on developing concrete mixtures that are suitable for 3D printing and investigating their properties throughout the printing process (Rahul et al. 2019; Kleshchevnikova et al. 2021). On the other hand, "design" and "fabrication" are critical aspects that highlight the integration of architectural and engineering considerations during the printing process. Studies in this field explore the potential for innovative forms and geometries made possible by 3D printing concrete while also aiming to optimize design parameters for effectiveness, accuracy, and constructability (Niemelä et al. 2019; Van Der Gaag et al. 2019).
Research topics under this component emphasized the integration of technological advancements into 3D concrete printing, bringing together digital manufacturing, automation, and advanced design techniques (Albar et al. 2019; Sakagami et al. 2020). They focused on optimizing the printing process, exploring robotic manufacturing, and leveraging digital design tools to improve the efficiency and accuracy of 3D concrete printing. Furthermore, the emphasis on sustainability shows the industry's growing dedication to environmentally friendly practices, with research activities aimed at generating sustainable concrete mixtures and construction methods.

3.2. CLUSTER 2: MATERIAL PROPERTIES AND PERFORMANCE

The second cluster reflects an important area of research in the context of 3D concrete printing, focusing on concrete materials and strength analyses (see Table 2). This cluster contains a wide range of keywords that examine the performance, composition, and performance of concrete mixtures, as well as their mechanical strength and durability.

An essential theme in this cluster is concrete mixes and compressive strengths. Keywords such as "cement", "mixture", and "compressive strength" stress the critical relevance of understanding the composition of 3D printing concrete and its ability to withstand compressive forces (Ilcan et al. 2022). The investigation of various cement kinds, with a focus on "Portland cement," is a significant component of the research in this cluster (Nerella et al. 2019; Lu et al. 2021). To obtain the desired strength and durability, it is essential to comprehend the function of cement in concrete mixtures and how it affects the material's ultimate qualities. Research on the "rheology" and "extrusion" behavior of 3D printable concrete is another major theme in this cluster. Rheological studies seek to evaluate the flow features and workability of concrete mixes, both of which have a direct impact on the printing process (Wangler et al. 2016). Keywords related to "material properties" and "fresh state" performance indicate research efforts focused on understanding the workability and early-age behavior of 3D printed concrete (Bos et al. 2021; Paul et al. 2018). Additionally, the "geopolymer concrete" and "inorganic polymers" keywords highlight the exploration of alternative cementitious materials with reduced environmental impact.

TABLE 2. Cluster 2 keyword list ordered by occurrence counts.

Cluster	Keyword	Links Count	Total Link Strength	Occurrences
2	cement	78	2415	327
	compressive strength	78	2255	302
	rheology	73	1512	196
	extrusion	73	1171	157
	mixture	73	1247	149
	yield stress	69	1138	146
	building	78	921	124
	mortar	70	921	117
	aggregate concrete	68	787	105
	portland cement	65	714	85
	composite	68	543	72
	geopolymer concrete	63	584	72
	elasticity	63	605	71
	hardened state	67	520	66
	fresh state	63	537	65
	silica	62	531	65
	hydration	60	472	64
	shears strength	64	451	59
	inorganic polymers	60	505	59
	limestone	57	436	51
	thermal insulation	57	310	48
	recycling	51	285	41
	viscosity	52	318	38
	material	55	236	34
	interlayer bonding	45	212	32
	clay	46	203	22
	plastic	41	153	19
	setting	38	152	18

3.3. CLUSTER 3: TECHNICAL EXECUTION AND PLANNING

Cluster 3, the smallest in terms of the number of keywords it contains, is a crucial component that sheds light on key aspects of mechanics and fiber reinforcement in the field of 3D concrete printing. In this cluster, a collection of interconnected keywords come together to underline the great importance of material behavior, structural integrity, and the impact of fiber reinforcements in enhancing the performance and reliability of 3D printed concrete structures.

TABLE 3. Cluster 3 keyword list ordered by occurrence counts.

Cluster	Keyword	Links Count	Total Link Strength	Occurrences
3	mechanics	78	1841	257
	tensile strength	72	1079	142
	fiber reinforcement	72	836	120
	reinforcement	68	701	101
	deformation	69	637	96
	pore structure	66	570	85
	steel fibers	57	393	56
	strain	60	359	54
	fracture	54	323	45
	polymer	61	365	43
	performance	58	279	39
	mold	61	237	35
	shotcreting	41	151	23
	image analysis	31	74	9

It is explicit that at the core of Cluster 3 lies a prominent research theme dedicated to exploring the potential of fiber reinforcement in 3D printed concrete with keywords such as "fiber reinforcement," "steel fibers," and "tensile strength" collectively emphasize the strong focus on enhancing the mechanical properties of printed elements, particularly tensile strength (Li et al. 2020). An important emerging theme is the investigation of the mechanical behavior of 3D printed concrete, paying particular attention to the "deformation" and "strain" properties (Xiao et al. 2021; Gebhard et al. 2023). The occurrence of "reinforcement" and "fracture analysis" related keywords emphasizes the significance of study into material formulation and structure optimization to enhance the structural integrity of 3D printed concrete (Kreiger et al. 2019; Pham et al. 2020). As the mechanical properties and overall performance of the material, including strength and permeability, are significantly influenced by the porous structure, the link between "performance" and "pore structure" in cluster 3 draws attention to research projects that aim to determine how 3D printing settings and material properties affect the internal pore structure of printed concrete (Liu et al. 2022). Additionally, Cluster 3 includes terms like "mold" and "shotcreting" that refer to work on advanced manufacturing methods for 3D printing concrete (Hack et al. 2020; Lachmayer et al. 2021). The adoption of various molds and shotcreting techniques, as well as construction applications, are studied by academics in this field to produce complicated geometries and effective material deposition.

4. Discussion

The field of 3D concrete printing is multifaceted, encompassing various interconnected and interdependent aspects. Extraction of pertinent information from the selected articles and a key theme classification was obtained. This classification differs from the research keywords clusters system created by VOSviewer. While VOSviewer visualizes the relationship between the keywords contained in the studies in the literature and the points touched upon by the studies, it does not focus on the main themes of the studies. A comprehensive reading of each article and general interpretation was conducted to identify and extract data related to four themes; material and mix properties, mechanical properties, construction plan properties, and printer properties.

Material and Mix Properties

"Material and mix properties" in 3D concrete printing encompasses research examining important aspects that underpin the successful additive manufacturing of concrete structures. This theme covers a wide range of research topics, including the development of sustainable alternatives to traditional concrete materials, the incorporation of reinforcements for improved mechanical performance, and the investigation of various materials and mixtures suitable for 3D printing. The keyword "concrete" acts as the core node for this theme, surrounded by keywords like "mixtures," "reinforcement," "geopolymers," and "sustainable materials." The primary goal of this theme is to create unique concrete formulas that are optimized for 3D printing while taking sustainability issues into account. In order to fully utilize the potential of various types of concrete bases for additive manufacturing techniques, researchers are looking into their unique properties and behaviors (Panda et al. 2019). Examples of these bases include geopolymers (Bong et al. 2019). Printed structures can be improved in terms of tensile strength and fracture resistance by focusing on fibers, thus ensuring long-term reliability and durability (Baz et al. 2021). Sustainable materials are becoming a major concern when it comes to addressing ecological issues and paving the way for environmentally friendly construction methods (Mohammad et al. 2020). Providing a framework for the investigation of advanced mechanical properties and printer processes, this topic is crucial to realizing the full potential of 3D concrete printing.

Mechanical Properties

The examination and improvement of important “mechanical properties” essential for the structural integrity and performance of the material, such as compressive strength, flexural strength, tensile strength, and fracture toughness, is the focus of the theme of mechanical properties in 3D concrete printing (Li et al. 2020). This shows that the evaluation of different mechanical parameters is prioritized to assess the strength and durability of 3D-printed concrete. To ensure the structural integrity and load-bearing capacity of printed concrete parts, researchers in this field are carefully studying important properties such as flexural strength, yield stress, compressive strength, and tensile strength (Paul et al. 2018). Mechanical property research is important to demonstrate the feasibility of 3D printed structures for real-world applications and to ensure compliance with industry requirements. Understanding the behavior of printed components under different loading conditions, such as flexural and tensile loads, helps in design optimization and reduction of potential structural vulnerabilities (Wolfs et al. 2018). Since mechanical behavior is greatly influenced by the materials, blends, and reinforcements used, the theme of mechanical properties works in conjunction with the theme of material and mix properties. By bridging the gap between material composition and mechanical performance, researchers are paving the way for strong and reliable 3D printed concrete buildings.

Printer Properties

The focus of the theme “printer properties” is on the technological aspects that underline the additive fabrication process as well as the properties of the 3D printing machinery used to fabricate concrete, including components such as nozzle, material extrusion, etc. (Xu et al. 2019). This theme refers to the crucial role of printing technology and robots in the precise extrusion and deposition of concrete. To identify suitability for specific construction tasks and project requirements, researchers are exploring the properties of different types of robots and machine technologies (Zhang et al. 2018; Tho and Thinh 2021). Advancements in machine improvement and development are aimed at enhancing printing speed, precision, and efficiency, thus pushing the boundaries of 3D concrete printing capabilities. The optimization processes of printer characteristics aim to achieve intricate geometries, seamless material deposition, and advanced automation, all crucial for successful and scalable 3D concrete printing projects. The growing interest in automated construction research indicates the increasing focus on autonomous and robot-assisted construction processes to optimize productivity and reduce human labor. Furthermore, the exploration of continuous and large-scale printing highlights efforts to scale the 3D printing process for constructing increasingly larger structures. The Printer Features topic is integral to the broader 3D concrete printing research, ensuring that the technology complies with the demands of the contemporary construction industry.

Construction Plan Properties

The “construction plan properties” theme revolves around the attentive design and planning aspects of projects involving additive manufacturing. This theme, demonstrates the incorporation of design research and digital fabrication within the field of 3D concrete printing endeavors. The keywords “digital fabrication" are connected to "design," "fabrication path of robots," and "geometric complexity," which occurred in the network visualization indicating the integration of digital design tools and parametric modeling in the 3D printing workflow within this domain, research papers focus on innovative approaches for generating intricate geometries and customized structures through design research. The fabrication path of the robot, printing region, and support structures were studied to optimize material flow and deposition, providing the precise realization of digital designs (Tay et al. 2019; Carstensen 2020). The emphasis on geometry highlights the importance of precise formwork considerations and the customization of the printing process to match the intended engineering and architectural vision. Researchers strive to enhance the safety, efficiency, and cost-effectiveness of 3D concrete printing projects by focusing on construction plan properties (García de Soto et al. 2018). By enabling perfect integration among material properties, mechanical performance, and the capabilities of the printing machines, this topic contributes to further studies and leads to the successful realization of innovative 3D concrete printing projects.

5. Conclusion

In recent years, there has been a significant increase in investments and research efforts in the field of digital fabrication, particularly in robotic 3D concrete printing. This systematic literature review provides a comprehensive analysis of the existing research literature on 3D concrete printing to identify patterns, trends, changes, and key themes in the field. The review methodology consists of an extensive search and screening of relevant literature, data extraction and analysis, and VOSviewer software for visualizing networks and connections between keywords.

The preliminary step of this research involved conducting a comprehensive data survey of the relevant academic literature from the Scopus and Cumincad databases in the field of 3D concrete printing using. The data collected from these databases were then meticulously analyzed through the VOSviewer software, which enabled a greater comprehension of the connections and correlations between keywords in the literature. This review identified three main clusters of keywords in the literature by employing keyword co-occurrence analysis with VOSviewer. Cluster 1 focuses on technical innovations and, highlights the core of 3D concrete printing research with the addressing the import of sustainability. Cluster 2 centers on material science and structural performance, emphasizing the significance of material behavior, concrete mixtures, and mechanical properties. Cluster 3 delves into structural behavior and performance analysis, critically assessing the strength, durability, and deformation characteristics of 3D printed concrete structures, highlighting the integration of design research and digital fabrication in the field of 3D concrete printing. This cluster addressed the creation of complex geometries, material flow optimization, and process customization in accordance with specific engineering and architectural objectives. The results of this comprehensive literature review demonstrate the multifaceted nature of 3D concrete printing. Through the analysis of selected articles and extracting key themes, four essential themes were identified: material and mix properties, mechanical properties, construction plan properties, and printer properties. These themes provide a deeper understanding for further investigation into the subject and offer a greater grasp of the 3D printing of concrete research environment.

Overall, this systematic literature review significantly contributes to the field of 3D concrete printing by offering a comprehensive analysis of the research literature and identifying trends, patterns, and key themes. The implementation of VOSviewer helped with the visualization of keyword connections and linkages, providing a holistic and methodical comprehension of the research context. The identified clusters and themes offer essential guidance for future research endeavors and contribute to evidence-based decision-making for researchers and practitioners in the field. This review serves as a tool for critical reading of the literature and assists in identifying the most influential and ineffective topics in the field by mapping the connections and developments within the research field.

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A FRAMEWORK PROPOSAL FOR NATURAL STONE PROCESSING WITH ROBOT ARM

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Abstract. Transforming raw stone materials into building elements and materials using traditional tools and methods has a long cultural history. As a reflection of computational design thinking, current production methods have been transferred to digital environments, making them suitable for processing and interacting with numerical machines. Physical media and production processes, which are difficult and slow to change and regulate, have been transferred to the digital environment and made programmable, changeable and open to algorithmic manipulation. The development of digital design and production methods in architecture has also paved the way for the digitalization of natural stone processing applications. Digital Fabrication methods are effective at all scales and stages of architectural processes. In subtractive methods, which is one of the digital fabrication methods, the material is shaped by subtracting parts from the main whole by cutting or milling. Processing with a robot arm is a subtractive production type, such as traditional stone carving. The process consists of the tool attached to the robot arm moving on the block. Along the path followed by the tool, the material is shaped by subtracting it according to the thickness, shape, step distance, progress speed, adjusted depth, and axis. In general, stone processing consists of two steps: rough processing that roughly removes the material layer by layer and fine processing that processes the remaining part precisely to produce a surface finish. The design of this production process creates a relationship between time and quality. At this point, simulation can be used to design the process based on the production tool before production and to provide feedback on the produced form by measuring it to the digital model after production. This study provides a comparative framework for the different processing steps of natural stone materials for robotic fabrication. The research includes collecting data on natural stone processing and robotic fabrication, drawing a framework for the geometric form to be processed, designing the stone processing process with a robotic arm, conducting simulation experiments, and analyzing simulation data. Since performing the experiments in physical would be restrictive in terms of cost and time, simulation technique was preferred. In this way, it was possible to conduct more experiments, and analyzes were strengthened.

Keywords: *digital fabrication; robotic fabrication; stonework; stone processing; simulation*

ملخص. لدى تحويل المواد الخام من الحجر إلى عناصر ومواد للبناء باستخدام الأدوات والأساليب التقليدية تاريخ ثقافي طويل. وكانعكاس للتفكير التصميمي الحوسبى، تم نقل طرق الإنتاج الحالية إلى بيئات رقمية، مما جعلها مناسبة للمعالجة والتفاعل مع الآلات الرقمية. تم نقل وسائط الوسائط وعمليات الإنتاج التي يصعب تغييرها وضبطها ببطء إلى البيئة الرقمية وتم جعلها قابلة للبرمجة، وقابلة للتغيير، ومفتوحة للتلاعب بخوارزميات. تطور طرق التصميم والإنتاج الرقمي في الهندسة المعمارية ممهد أيضًا الطريق للتصدي للتطبيقات الرقمية لمعالجة الحجر الطبيعي. تعتبر طرق التصنيع الرقمي فعالة على جميع المقاييس ومراحل العمليات المعمارية. في طرق الطرح، وهي إحدى طرق التصنيع الرقمي، يتم تشكيل المادة عن طريق طرح أجزاء من الكل بقطع أو تفريز. معالجة بذراع الروبوت هي نوع إنتاج خافض مثل نحت الحجر التقليدي. تتكون العملية من الأداة المرفقة بذراع الروبوت تتحرك على الكتلة. على طول المسار الذي تتبعه الأداة، يتم تشكيل المادة عن طريق خفضها وفقًا للسماكة والشكل ومسافة الخطوة وسرعة التقدم والعمق المعدل والمحور. بشكل عام، تتكون معالجة الحجر من خطوتين: المعالجة الخشنة التي تزيل المادة بشكل تقريبي طبقة بعد طبقة والمعالجة الدقيقة التي تعالج الجزء المتبقي بدقة لإنتاج تشطيب سطحي. تصميم هذه العملية الإنتاجية يخلق علاقة بين الوقت والجودة. في هذا النقطة، يمكن استخدام المحاكاة لتصميم العملية استنادًا إلى أداة الإنتاج قبل الإنتاج وتوفير ردود فعل على الشكل الذي تم إنتاجه من خلال قياسه على النموذج الرقمي بعد الإنتاج. توفر هذه الدراسة إطارًا مقارنًا لخطوات معالجة مواد الحجر الطبيعي المختلفة للتصنيع الروبوتي. تشمل البحث جمع البيانات حول معالجة الحجر الطبيعي والتصنيع الروبوتي، ورسم إطار للشكل الهندسي الذي سيتم معالجته، وتصميم عملية معالجة الحجر بذراع روبوتي، وإجراء تجارب المحاكاة، وتحليل بيانات المحاكاة. نظرًا لأن إجراء التجارب في الواقع يمكن أن يكون مقيدًا من حيث التكلفة والوقت، تم تفضيل تقنية المحاكاة. بهذه الطريقة، كان من الممكن إجراء المزيد من التجارب، وتم تعزيز التحليلات.

الكلمات المفتاحية: *التصنيع الرقمي، التصنيع باستخدام الروبوت، أعمال حجرية، معالجة الحجر، محاكاة.*

1. Introduction

In the field of architecture, digital advancements have not only influenced design concepts, tools, and methods but have also led to a transformation in production techniques, shifting from file-to-factory approaches (Gershenfeld, 2012; Carpo, 2013). Digital fabrication encompasses both the design and production processes, where data from CAD software is realized using CAM tools. It requires a designer's familiarity with digital fabrication tools and methods to fully realize the design's intentions (Schodek et al., 2005; Scheurer, 2010; Kolarević, 2008; Iwamoto, 2009). As a result, the role of architects has expanded to be increasingly involved in the production process itself.

Digital fabrication methods have created a versatile environment for theoretical and applied research, becoming effective in all scales and stages of architectural processes. The precision and adaptability of industrial robotic arms in complex and extensive production lines have made them ideal tools for digital fabrication in architectural design. The advent of industrial robot arms in the field of architectural design and production has brought about various research topics such as automating actions, improving process quality, optimizing operations, and enhancing precision. Robot arms, equipped with specialized end-effectors for processing different materials, offer advantages for both the industry and designers, enabling high precision and repeatability at a speed beyond human capabilities.

In the context of materials, research in the field of digital fabrication in architecture includes alternative and sustainable material studies, optimization of existing materials, advanced recycling applications, and investigations into different construction techniques using existing materials (Şen-Bayram, 2021). Integrating robotic fabrication into traditional areas like stone carving can increase the production scale without compromising geometric complexity. However, limited computational research specifically focused on stone materials, categorizing and simulating robotic processing techniques. The cost of tooling and the risk of breakage when performing intensive milling operations on hard materials like stone are the primary reasons for the focus on softer materials like wood, foam, clay, and concrete. Nevertheless, in an effort to avoid these financial losses, companies in the stone carving industry have turned to CAD/CAM workflows and robotic fabrication to increase production speed and maintain competitiveness in a market with rising material and labor costs, creating their own "new Renaissance" by embracing the skill of industrial robots (Dorfman, 2018, in citation Lopez).

This situation creates a notable research area in the literature. To address the complexity and multidimensionality of this process, it is essential to formulate the solution space with visually definable rules based on combinations of components and functions that the designer has control over during production. Therefore, this paper aims to present an optimization framework that can harmonize performance criteria for understanding the cause-and-effect relationships of robotic stone processing and optimizing the process. This research is expected to expand the existing solution space and contribute to the literature on robotic fabrication in the field.

The case study consists of two parts: the comparison of the processing times as a result of using previously produced stones with the same geometric shape but different degrees of hardness for the purpose of examining the application process, and the comparison of the simulation experiments with a geometric relationship between them, but with the assumption that different models are used with the same stone, in order to examine the effect of geometry on the processing processes.

2. Background

The concept of fabrication, defined as the physical production of a digital object through the automation of a series of steps or processes (Mitchell & McCullough, 1995), has gained a central position in the field of architecture with its ability to transform data into things and things into data (Gershenfeld, 2015), redefining design and production processes (Carpo, 2017). Industrial robotic arms, which have gradually integrated into the realm of architectural digital fabrication, have expanded the existing production capacities towards a robust and versatile performance due to their multi-axis design, the capability to reach any point in the range of motion, the increased production method capability with different end-effectors, and the enhancement of performance with sensors and/or a rotary table (Keating, 2012). Over the past decade, industrial robots have been widely used in various manufacturing processes, performing repetitive tasks in thousands of factories worldwide. Regardless of the robotic fabrication method used, there are numerous alternatives depending on the material, method, tool nature, etc. However, robotic subtractive stone processing where the material is shaped by cutting or processing to remove excess parts from the main block, stands out for its resemblance to traditional stone processing methods.

Traditional stone processing techniques have been developed over thousands of years by skilled artisans and stone masons, requiring technical knowledge and expertise to cut, shape, and polish stones according to their type and intended use. The process involves cutting the stone to desired dimensions, shaping it to the required form, and polishing its surface to reveal its natural colors and patterns, after which it can be installed or used as a finished product. Stone artisans, with their years of experience and manual skills, understand the characteristics of natural stone and use this knowledge to achieve the best results, reflecting the stone's texture, colors, and patterns in the final product. Apprentices in this process learn through observation and hands-on experience, with masters teaching the structural and physical properties of stones through practical demonstrations.

In parallel with traditional methods, technological advancements have led to computer-controlled fabrication processes in the industry. Similar to traditional methods, milling begins with rough cutting and progresses to fine finishing. The initial rough cut is typically made with a saw blade from the stone's outer surface to the designed model, resulting in rough edges. For the second rough cut, a disk-shaped diamond tool is used to shape the stone. Subsequent milling steps are performed with smaller tools in sequence. Due to the high loads required to process the stone, the cutting depth of the tools is limited, and the machine needs to move at a slower pace to prevent overloading and tool breakage. While CNC approaches offer advantages in precision and overall capacity, industrial robotic manipulators offer unique potential in fabrication due to their flexibility and portability (McGee, 2014).

The process of robotic fabrication involves transferring digital information from computer-aided design tools to a robot arm specialized in manufacturing, resulting in the creation of physical objects through the robot arm's precise movement on the material. Factors such as the tool's diameter, shape, step size, cutting speed, working depth, and defined axis determine the route along which the material is removed, resulting in the desired shape. Within this complex and multi-layered process, there exists a layered and intricate relationship between material hardness, processing time, surface resolution, and surface quality. Designing this production process establishes a relationship between time and quality. Simulation can be used to design the process before fabrication, providing feedback through digital models after fabrication, enabling controls, preventing potential issues, and saving time and costs.

The use of robot arms in the stone processing industry can increase automation, reducing costs while contributing to the safety and health of human workers. The properties of the stone are crucial in the robotic stone processing method. Thus, depending on the characteristics of the stone, different research methods can be applied in investigating the use of robot arms for stone processing. For example, the hardness and durability of the stone can affect the type of cutting tools and processing speed used by the robot arm. Therefore, considering the physical properties of the stone, the selection of the cutting tool the robot arm will use may be necessary. In addition, the fragility of the stone can complicate the processing and may cause cracks or other defects during the process. As a result, researchers can conduct experiments to optimize the movements of the robot arm to prevent breakages during stone processing and develop new techniques for stone processing to avoid fractures.

Robot arms are versatile tools capable of performing multiple functions with their interchangeable end-effectors and can work in complex production or assembly lines under the control of a central system. Depending on the type of robot arm, it can reach an area up to 3 meters in diameter. The control mechanism up to 6 axes can be extended to 7 axes by adding an external rotating table to the robot arm or by using a rotary table to process the material. The rotary table is a precise positioning device synchronized with the system, enabling precise rotation around an axis. The workpiece can be fixed to the table for various operations such as processing, cutting, or drilling.

In general, stone processing consists of two steps: rough processing, which removes the material roughly layer by layer, and fine processing, where the tool precisely processes the remaining part to achieve surface finishing. The initial rough processing cuts to a certain depth from the outside of the surface. This leaves a very rough surface. Subsequent milling is done with smaller tools to mill the remaining stone. The size of the tools directly influences the depth of cutting, and the machine must move slowly to prevent overloading and breaking the tool.

Current research in robotic stone carving is more fabrication-oriented, with less focus on simulation (Brugnaro et al., 2019). The Digital Stone Project's 2018 workshop exemplifies the development of a framework for interactive modeling to shape a wide, undulating, and ultra-thin marble surface with great precision (Figure 1). Milling operations were programmed with CNC software and carried out using a 6-axis industrial robotic arm with an added rotary table to achieve 7-axis milling. The milling process included initial rough carving followed by detailed carving, taking approximately 36 hours in total (Lopez, 2022).

Figure 1. Digital Stone Project digital model (left), processed material (right) (Lopez, 2022).

Recent research in this area focuses on adaptable robotic stone carving. In a study addressing unpredictable material behavior, a feedback loop with sensors and an improved tool was utilized. In this experiment, both the robot and sensor function as the client, collecting data, while the server updates the integrated model between carving iterations (Shaked et al., 2020). After each carving, the digital model is updated and the process is repeated until the target geometry is achieved (Figure 2). This study emphasizes the importance of high-resolution scanning, developing a factory-grade end-effector, and precise actuation to adapt to varying material scenarios and produce complex architectural elements using a range of uncertain materials.

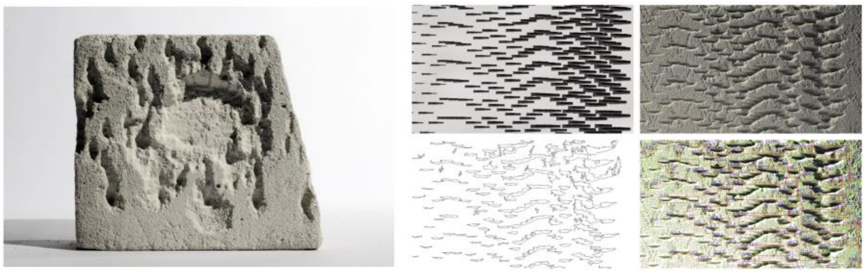

Figure 2. Processed material (left), toolpath(right) (Shaked et al. 2020).

3. Methodology

The research focuses on implicit robot control in industrial stonework for a bottom-up design process. In addition, by simulating the machining process with the robot arm in a real-time programming environment, it is aimed to be able to virtually prototype the complex interactions of materials, forms and robots. As a result, this study aims to support the designers to gain competence in this field by investigating the process of processing natural stone material with the robot arm and to enable them to discover new opportunities that allow the use of natural stone materials in architectural design.

By working with fabrication strategies defined specifically for production, designers can program individual toolpath command files that are transformed into geometry-specific robot control data. Simulation is used for modeling the process based on the production tool and path before production and for providing feedback by measuring the manufactured product with the digital model afterward. Users can manipulate external data input or internal fabrication parameters, simulate the resulting robot toolpaths in real-time, and make changes between different tool positioning strategies in real-time to prevent collisions. Changes in tool paths can be observed simultaneously, allowing for dynamic collision and accessibility control. Simulation tools enable designers to optimize the use of the working area by analyzing the robot's pose, general accessibility conditions, collisions, and axis limits in real-time, based on the designed digital model.

Simulation and analysis defining the geometric form according to toolpath strategies create a design from bottom to top. Feedback is created by identifying collision situations and inadequate tool performance, enabling timely intervention (Braumann & Brell-Cokcan).

Recently, several software projects, including KUKA RPC (Braumann & Brell-Cokcan, 2012) and HAL (Schwartz, 2013), have attempted to include robots in design workflows by providing interfaces that help designers organize robotic procedures. These software packages assist designers in simulating robot behavior in real-time and working in visual programming environments. While essential to enable designers to explore the capabilities of robots in architecture and design, gains can be increased by defining and directing the "design domains" of these machines at lower abstraction levels (Bidgoli & Cardoso-Llasch, 2015). For this reason, in order to simulate robot movement, create a tool path for robot operation, and visually understand the relationship between robot movement and produced forms interactively, SprutCAM, a CAM software used to control KUKA, ABB, and UR industrial robots, was used.

4. Case Studies

The research focuses on implicit robot control and simulation modeling in industrial stone processing for a bottom-up design process. The aim is to virtually prototype the complex interactions of material, form, and robots by simulating the processing process as a digital model in a real-time programming environment.

The research consists of a case study to examines the effect of geometry on processing processes by comparing simulation experiments with geometrically related but different models using the same type of stone.

The study on implicit knowledge in stone processing is carried out by creating a 7-axis robot arm model that supports the research as a subtractive manufacturing method. The mentioned 7-axis system is utilized in both physical experimental processes and simulation calculations by adding a 6-axis robot arm and an external rotary table. The material is shaped by generating the robot toolpath with construction parameters such as the tool tip, tool size, flow direction, cutting depth, processing speed, approach distance, part definition, surface geometry, and processing boundaries. The code, consisting of alphanumeric characters defining the coordinates held by the toolpath, as well as specific movements, is described through a machine language called KRL, unlike the G-Code machine language used in other digital fabrication tools. Various CAM tools have their own specialized CAD software, providing simple and fast toolpath generation. In this context, the SprutCAM program, a CAM software used to control KUKA, ABB, and UR industrial robots, is utilized to simulate robot movement, create a toolpath for robot operation, and visually understand the relationship between robot movement and produced forms interactively.

Through these tools, users can participate in the production process by selecting or defining manufacturing parameters in visual interfaces based on the desired material forms as digital models. This process allows various and diverse material shapes belonging to a single digital model to be obtained since each operation emerges as the result of another operation in the design process.

The primary step in the CAM interface for creating a basic toolpath for a digitally modeled geometry usually involves setting up the robot arm that will perform the production. One of the existing robot systems can be selected within the program, or customized systems can be added. Following the selection of the robot arm, the digital object, the workpiece to be processed, the fixture that holds the part, and any parts that should not be processed are defined. For the field study, an external rotary table is used to place the workpieces since it was found suitable to use this rotary table for the parts. With the placement of this rotary table, the first stage of the setup is completed.

As previously mentioned, processing processes consist of two main stages: rough machining and finish machining. Each of these two main processes contains various operations within itself. For this reason, even to process a single part, it is decided how the robot arm will approach the workpiece from different directions, depending on the geometry that will be processed.

One reason for choosing the SprutCAM interface in the field study is its inclusion of various pre-defined operation options for the user. Depending on the desired geometry, operations used for different purposes may require additional part definitions in some cases. Points, lines, planes, or three-dimensional surfaces of digital models can be used in different combinations to make part definitions according to the type of operation. Additionally, the flow direction of the tool tip on the material surface and the pattern of this direction can be pre-set as linear, spiral, etc. Moreover, the step distance of the tool defined as the distance between the paths in a toolpath model can be set either as very small distances to obtain smooth surfaces without any material left on processed areas or according to the designer's preference for the surface to be created on the material.

To finalize and create the toolpath, parameters such as shape, diameter, length, cutting length, and holder type of the tool tip must be defined. If some areas, such as corners and concave surfaces, are smaller than the tool diameter, it will not be possible to process these areas with the tool. As a result, the material shape that will be obtained will be different from the initial surface geometry in the digital model.

After the creation of the toolpath, the defined operations are calculated one by one to reveal any potential issues for each operation. If there are no problems in the operations, all processes are simulated to gain a basic idea about the likely shapes that will emerge before production and to verify error-free operation of the toolpath. Designers can experiment with different parameters for the digital models before actual processing to conduct research on form-related issues.

In conclusion, different geometric models can be created with toolpaths composed of various parameters from a single digital model. Due to the existence of many other parameters that control the toolpath and affect the formation of resulting shapes in robot arm processing, a comprehensive discussion of the production is beyond the scope of this study.

The initial experiments focused on surface area, geometric detail, and processing time. The research was developed by branching into two directions: one emphasizing an increase in geometric detail while keeping the surface area constant, and the other focusing on an increase in both geometric detail and surface area in a specific proportion. The process began with the creation of a 20x20 cm cube using Rhino 7 in the Grasshopper environment, and each step involved subtracting a 4x4 cm cube geometry from this cube. In the first stage of the experiment, the gradually subtracted small cubes were removed from the corner positions of the initial geometry to maintain a constant total surface area. In the second stage of the experiment, the subtracted small cubes were removed in a way that aligned with the upper surface boundaries of the initial geometry, resulting in a certain increase in surface area for each step.

Throughout the simulation experiments, the same toolpaths were applied to each differentiated digital model, assuming the use of the same stone material. This approach aimed to minimize the number of parameters and facilitate the comparison of processing times. As depicted in Table 4.1, a more detailed analysis was conducted by comparing processing times, types of stone, and geometries (Figure 3).

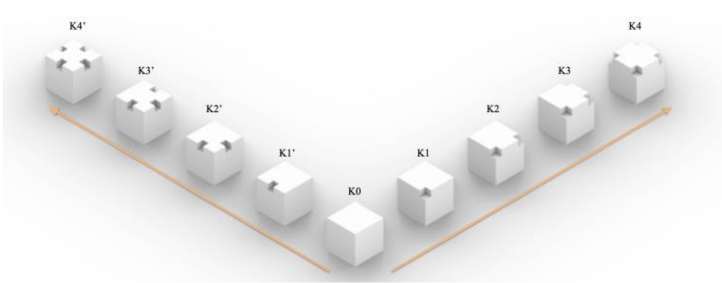

Figure 3. Geometries.

TABLE 1. Simulation Results

Design			Material		Set-up					Time
Geometry	Surface Area	Sub	Workpiece	Property	Robot	Rotary Table	Tool	Milling Depth	Milling speed	Duration
K0	2000 sqm	6 surface, 8 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	06h 56m
K1	2000 sqm	9 surface, 14 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 04m
K2	2000 sqm	12 surface, 20 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 06m
K3	2000 sqm	15 surface, 26 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 11m
K4	2000 sqm	18 surface, 32 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 16m
K1’	2032 sqm	10 surface, 16 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 02m
K2’	2064 sqm	14 surface, 24 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 06m
K3’	2096 sqm	18 surface, 32 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 08m
K4’	2128 sqm	22 surface, 40 point	9261 m3	Same	Kuka KR120	Yes	20mm cylindric mill	30mm	200 mm/s	07h 10m

5. Conclusion and Future Works

There is a strong connection between the process (methodology) and operation (application) because they can potentially encourage a significant alignment or connection between the artifact and its context (user or environment) (Oxman, 2007). In cases where production methods and material considerations are incorporated into the design process only as final design solutions, rather than encouraging explorations that are inherently generative, a hierarchical approach tends to prevail. While processing traditionally appears as a final step in execution, within digital fabrication methods, it goes beyond simply pressing a power button. "From File to Factory" protocols (Schodek, 2005) have indeed propelled our vision forward as designers in terms of efficient CAD/CAM processes, yet the reverse, "from factory to file," has not been given due consideration (Oxman, 2007). The selection of materials and production methods are factors that need to be predetermined, guiding the design from inception to completion, both in terms of the artifact and the process.

Overall, by combining traditional craftsmanship with robotic technologies and digital production, innovative and efficient designs can be achieved. The use of robot arms for stone processing has the potential to enhance automation, reduce costs, and contribute to the safety and health of workers in the industry. However, understanding the properties of the stone and the interaction between the robot arm and the material is critical to ensuring successful and efficient stone processing.

Physical experimentation would be restrictive in terms of cost and time, so the simulation technique was pursued. This allowed for more experimentation and strengthened the analysis of end products. Although simulation experiments help prevent collision and tool path errors in the processing process before it starts, there can still be issues that are beyond the capacity of these experiments. Problems like the wear and tear of tool tips used in processing stone blocks by the robot arm, if not detected and addressed early, can alter the final result. Precautions can involve the use of diamond-tipped tools and mills scanned with a laser scanner to detect wear. Other hardware-related issues can include machine stoppages and failures in water pipes or tool breakage.

For such a complex and multi-layered process, redefining the solution space that can be visually defined by rules and manipulations based on combinations of components and functions through computational models can create a facilitating environment, enhancing the designer's control over production in architectural design.

With such research, it is believed that the existing solution space in the field will expand and contribute to the literature on robotic fabrication, which is novel in the research subject within the current application area.

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5.A.

VIRTUAL REALMS AND MULTIVERSE ENVIRONMENTS - I

COLORCRAFT: A MIXED-INITIATIVE SYSTEM FOR SUPPORTING CREATIVITY IN COLORING VISUAL PATTERNS

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Abstract. Focusing on generating, using, and exploring color schemes and applying them to visual patterns, this paper questions how co-creation systems can support artists' creativity in coloring and explore possible UX features for such systems. Through an applied research project, we demonstrate a prototype system, *ColorCraft* that incorporates mix-initiative interaction methods building on an extensive literature review and expert interviews. Through *ColorCraft*, we propose possible UX techniques for facilitating the generation of color compositions and assigning colors to visual patterns, allowing for the exploration of alternative pattern colorings. We aim to enhance co-creative processes and provide tool features for applying colors on patterns in, e.g., graphics design, architecture, and interface design. The formative evaluation of the prototype shows promising feedback and insights for improving coloring applications. The study contributes to our understanding of problem characterization of coloring, and the artists' expectations from tools that will augment their creative exploration of pattern coloring.

Keywords: *Pattern coloring, mixed-initiative system, coloring applications, generative design*

ملخص. من خلال التركيز على إنشاء أنظمة الألوان واستخدامها واستكشافها وتطبيقها على الأنماط المرئية، تتساءل هذه الورقة عن كيفية دعم أنظمة الإنشاء المشترك لإبداع الفنانين في التلوين واستكشاف ميزات تجربة المستخدم المحتملة لمثل هذه الأنظمة. من خلال مشروع بحث تطبيقي، قمنا بعرض نموذج أولي لنظام ColorCraft الذي يشتمل على أساليب تفاعلية مختلطة مبنية على مراجعة واسعة النطاق للأدبيات ومقابلات مع الخبراء. من خلال ColorCraft، نقترح تقنيات تجربة المستخدم الممكنة لتسهيل إنشاء تركيبات الألوان وتعيين الألوان للأنماط المرئية، مما يسمح باستكشاف ألوان الأنماط البديلة. نحن

نهدف إلى تعزيز العمليات الإبداعية المشتركة وتوفير ميزات الأدوات لتطبيق الألوان على الأنماط، على سبيل المثال، تصميم الرسومات والهندسة المعمارية وتصميم الواجهة. يُظهر التقييم التكويني للنموذج الأولي تعليقات ورؤى واعدة لتحسين تطبيقات التلوين. تساهم الدراسة في فهمنا لتوصيف مشكلة التلوين، وتوقعات الفنانين من الأدوات التي من شأنها زيادة استكشافهم الإبداعي لتلوين الأنماط.

الكلمات المفتاحية: *تلوين الأنماط، نظام المبادرة المختلطة، تطبيقات التلوين، التصميم التوليدى.*

1. Introduction

Geometric patterns refer to the repetition of multiple design elements within a given design area. They find extensive application in various design fields, particularly in graphic design. These patterns are commonly used in packaging and play a significant role in establishing a brand's identity. Additionally, colors serve as vital components of visual patterns, enhancing their impact and effectiveness.

Creating visually appealing coloring applications is essential for achieving pleasing patterns. A well-designed coloring system to support creativity should be versatile and adaptable to different color applications (Shneiderman et. al 2005). It should provide a range of suggestions to help unsure color artists to discover color combinations consistent with the coloring principles while allowing for personalized recommendations based on different aesthetic preferences, enabling the artists to achieve their desired style. Additionally, the system should give users the ability to refine the coloring criteria and influence the suggestion process through intuitive controls (Lin 2013).

Color creation and applications can be achieved by manual or generative methods. Manual coloring methods offer promising processes for deciding on a color palette and manipulating colors freely under the color artist’s control, e.g., by selecting a color wheel, using a color picker, or entering color codes. However, manual coloring remains limited to the exploration of different alternatives rapidly. Generative coloring systems, on the other hand, offer an iterative process that allows users to explore alternatives, experiment with color combinations, and enrich the color composition. These systems can be algorithmic- or machine learning-based, and therefore provide limited user intervention. Integrating manual and generative methods under a mixed-initiative system can augment an artist’s creativity. Manual coloring tools lack agile exploration of alternatives, while algorithmic coloring tools may require more user control and intervention. Therefore, we aim to explore answers to the following research questions:

RQ1: How can mixed-initiative systems facilitate a seamless transition between manual and generative (co-creation) pattern coloring methods?

RQ2: What are the significant challenges inherent in employing AI algorithms for pattern coloring, and how do they affect user experience and creative outcomes?

RQ3: What are the possible pattern coloring features that can be integrated into mixed-initiative systems to empower coloring artists, and how do they foster creativity and exploration?

According to the research questions, we designed a mixed-initiative system prototype called *ColorCraft* that aims to give the coloring artist agency for exploration that combines multiple techniques in the pattern coloring process by bridging the gap between manual coloring and generative coloring systems presented in the literature. This prototype relies solely on interaction design, assuming that its generative features will function based on existing AI algorithms. The core focus of the prototype lies in facilitating a seamless and intuitive user experience for coloring artists to express their creativity effortlessly.

After reviewing both non-generative and generative coloring tools, we identified different coloring methods that can enhance the artist's agency and augment creativity by supporting exploration and search. We demonstrated the coloring methods on example patterns and the application of color using clustering options in a case study. A comparison feature was added to support generating more pattern alternatives among the favorite color pattern designs generated. Furthermore, a sharing feature was added to support collaboration for receiving feedback on pattern coloring.

We adopted the design study methodology for domain problem characterization and requirements elicitation combined with an agile software development process for developing *ColorCraft* The domain characterization was based on an extensive literature review of visual patterns, coloring, the underlying coloring theories, and interviews with coloring artists. *ColorCraft* also aims to contribute to the artists' learning process of coloring techniques and experience the application of coloring in their practice. Our findings will contribute to a better understanding of mixed-initiative systems that support designers' creativity and improve the process of creating visually appealing patterns colored.

2. Background Information

2.1. COLOR THEORY AND COLORING

Color theory is a fundamental aspect of design that explores the principles and effects of color on visual perception and communication. It provides a framework for understanding how colors interact, harmonize, and convey meaning, enabling designers to create impactful and visually appealing compositions. By understanding the principles of color theory and its applications, designers can make informed decisions when choosing and combining colors.

Color relationships play a vital role in design composition. The color wheel, a visual representation of the color spectrum, serves as a foundation for understanding the relationships between the parameters defining colors. Primary colors (red, blue, and yellow) form the basis for all other colors, while secondary colors (orange, green, and violet) are created by mixing primary colors. Tertiary colors result from mixing primary and secondary colors. Complementary colors, which lie opposite each other on the color wheel (e.g., red and green), create a strong contrast and are used to draw attention or create visual interest. Analogous colors, on the other hand, are adjacent to the color wheel and produce harmonious and cohesive color schemes.

The applications of color theory from graphic design and branding to interior design and web design play a critical role in shaping experiences with the artifacts colored and the indented visual impact. Designers use color theory principles to establish a hierarchy of information, direct attention to specific elements, and create memorable and engaging designs. Additionally, color theory is often used in marketing and advertising to evoke desired emotions and establish brand identity and recognition.

2.2. COLOR SCHEMA AND PALETTE GENERATION

Generative coloring and applications have gained significant attention in the fields of design, art, and computer graphics (Rao and Qiu 2022). The literature presents innovative approaches using algorithms and computational techniques (Gero 2000) to automate the generation of aesthetically pleasing color schemas. We reviewed the literature to explore available techniques for generative coloring and evaluate their advantages and disadvantages. A range of methodologies has been proposed for generating color palettes automatically. These include rule-based approaches (Gramazio et al. 2017; Bergman 1995; Tennekes and Jonge 2014), where predefined rules determine color compositions; machine learning techniques, which utilize large datasets to learn color compositions and preferences; and interactive systems, which allow users to manipulate and edit parameters to generate novel color combinations.

2.2.1. Machine Learning Techniques

Bahng et al. (2018) used text-based color palette generation with a deep learning model. It uses a dataset of 10,183 text and five-color palette pairs to train their model. Words vary concerning their relationships with colors;

some words are direct color words (e.g., pink, blue, etc.) while others evoke a particular set of colors (e.g., autumn or vibrant). (Bahng et al., 2018) The advantage of their model is to generate multi-word text where other text-based palette generators use limited words. Kobayashi‘s Color Image Scale uses 180 adjectives to describe the three-color palette. As the number of color boxes increases, the number of color combinations increases, so that it gives flexibility to the artist. It allows them to experiment with different color combinations, explore new harmonies, and push the boundaries of traditional color schemes. If text is better described with a wide range of words, the text input becomes more sophisticated which incorporates with artist more and supports creativity.

2.2.2. Algorithmic and Rule-Based Techniques

In the work of Stahlke and Zaman (2018) on Choromotype, image sampling, and random variation were used to create multiple palettes. ColorCraft includes a gallery interface that allows designers to quickly create, manipulate, and save a variety of color schemes. In this tool, there is a gallery interface that is constantly shown on-screen alongside the active palette, color editing, and filter selection panels (Stahlke and Zaman 2018). This interface eliminates the limitations between generative tools and the user, allowing the artist to be actively involved in the creative process by displaying and controlling multiple interchangeable palettes. The interface supports the artist's exploration process by facilitating the quick interchangeability of palettes.

2.2.3. Interactive, Manual Techniques

While interactive methods achieve satisfactory results in color palette generation, a limitation is that users need to have a certain level of artistic ability. Wijffelaars et al. (2008) proposed a gradient-based color palette generator called Magnaview. By allowing manipulation of color palettes with a limited set of parameters, the user interface becomes simplistic and enables users to generate a wide variety of palettes. The system allows users to manually manipulate and edit colors through parameter changes, providing control to the artist.

Meier et al. (2004) explored multiple interactive coloring tools, such as image sampling, palette browsing, gradient mixing, and randomized colors, applied to image composition. By offering different interactive tools, they support different artistic styles, creating numerous opportunities for artists to experiment and explore their creativity.

In summary, generative color palettes have significantly impacted the fields of design, art, and computer graphics by leveraging algorithms and computational techniques. Machine learning approaches, such as Bahng et al.'s (2018) text-based palette generation model, demonstrate the potential of using deep learning algorithms to generate multi-word text descriptions and provide more sophisticated input options for artists. Rule-based and algorithmic methods, exemplified by Stahlke and Zaman's (2018) Choromotype, utilize image sampling, random variation, and gallery interfaces to enable quick creation, manipulation, and exploration of multiple color schemes. Interactive systems, as proposed by Wijffelaars et al. (2018) and Meiner et al. (2004), provide users with control over color palettes through parameter changes and a variety of interactive tools. While these generative color palette techniques have shown promising results, the possibility of experts and designers searching for color combinations through only one method is not enough. In addition, it is important to note that users may still require a certain level of artistic abilities to achieve desired outcomes.

3. Methodology

We developed *ColorCraft* combining the coloring methods discussed in the literature following the principles for Creativity Support Tools (Shneiderman 2005; Shneiderman et al. 2009) as the main high-level requirements for its mixed-initiative system features. For example, *ColorCraft* is accessible to artists with a variety of coloring needs or styles while enabling the exploration of coloring applications without prematurely committing to a particular solution. Its design aims to consider the needs of novices and to provide functionality to enable experts to perform what-if scenarios. These features are derived from a critical review of the methods employed by the existing coloring tools as research prototypes of applications used in practice. Consequently, the first phase of the research method involved extensive research on available tools, critically evaluating their functionality, and identifying key techniques. In the second phase, we develop tool features following *ColorCraft* analysis and findings from the literature. We developed the prototype following an agile methodology using use cases and user stories evolved incrementally.

The evaluation of *ColorCraft's* features was part of the agile method which was concluded by a focus group review study as its formative evaluation involving 5 artists and designers with experience in coloring and existing tools. The participant joined the study by invitation. After presenting a series of tasks on creating coloring schemas and their application to a geometric pattern, the participants were asked to provide their feedback on their experiences with *ColorCraft.*

The focus group study started with general questions about the participants' background, followed by exploratory questions about the participant's experience with the features of the system demonstrated on sample tasks on *ColorCraft*. The exploratory questions were based on the cognitive dimension's framework by Green and Blackwell et al. (2001) addressing a broad-brush review of tool features considering cognitive dimensions such as viscosity, visibility, early commitment, latent dependencies, expressing the role, prone to error, abstraction, secondary representation, proximity of mapping, coherence, disorganization, and rigid mentality (Green and Blackwell et al. 2001). Finally, the exit questions covered any concerns or suggestions that may have been missed. Based on the participants' comments and feedback, the proposed tool was evaluated and discussed.

4. Approach

4.1. PROBLEM DESCRIPTION

Generative design tools are to support creativity, some features of these tools are limiting designers in terms of mental effort, narrow templates, or restricted allowance whereas, manual coloring tools are user-oriented but lack alternatives (Figure 1). In this study, a tool based on CST principles is proposed. Through this research, the aim is to enhance designers' creativity in coloring visual patterns through a proposed mixed-initiative tool that provides the iterative exploration process. Therefore, the intent is to develop a better understanding of mixed-initiative systems that support designers' creativity and improve the process.

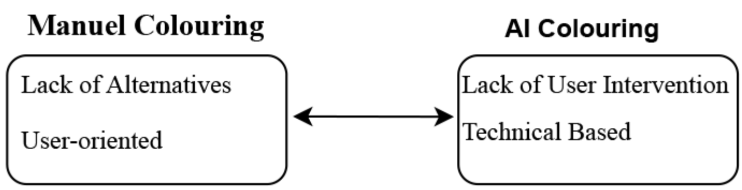

Figure 1. Comparison of AI coloring and manual coloring.

5. Implementation

ColorCraft comprises two primary features: the color palette options and the grouping of the geometries of patterns for color palette application.

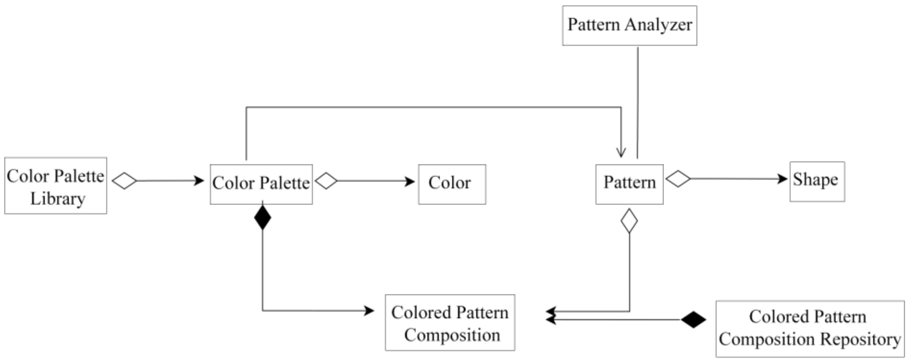

Figure 2. A proposed domain model for coloring patterns in a co-creation system showing the relationship between coloring artefacts and patterns. The two main domain objects are Color Palette and Pattern. The system presents UX features for creating and applying Color Palettes on any Pattern object and persistently storing the result for reuse.

5.1. CREATING COLOR PALETTE OPTIONS

The color palette creation section offers users four distinct coloring options. These options include blending, manual color palette creation, creating a color palette by specifying a keyword, and extracting colors from an example photo (Figure 3).

5.2. APPLYING COLOR PALETTE TO A PATTERN

We divided the geometry clustering based on sub-shape area, the distance between sub-shapes, and the geometric similarity of sub-shapes. Using these grouping techniques, artists can create new compositions by manipulating shape selection on a pattern dynamically. *ColorCraft* allows to change a composition's coloring as clustering techniques change and to generate variations from a completed composition (Figure 4).

5.3. INTERACTIVE FEATURES

ColorCraft includes a histogram overlay applied colors on the sub-shapes in a pattern. Selecting a column in the histogram, *ColorCraft* colors the corresponding clustered shapes on the pattern. This interactive feature enables users to inspect and visualize the coloring data within the pattern. As a result, users may gain insight into clustering and have control over grouping options. Selecting the colors displayed under the histogram enables experimentation by changing color position and distribution. The sliders on the histogram allow adjusting or fine-tuning the color data intervals. All such features are simultaneously applied to the pattern, enhancing the users' interaction experience (Figure 5).

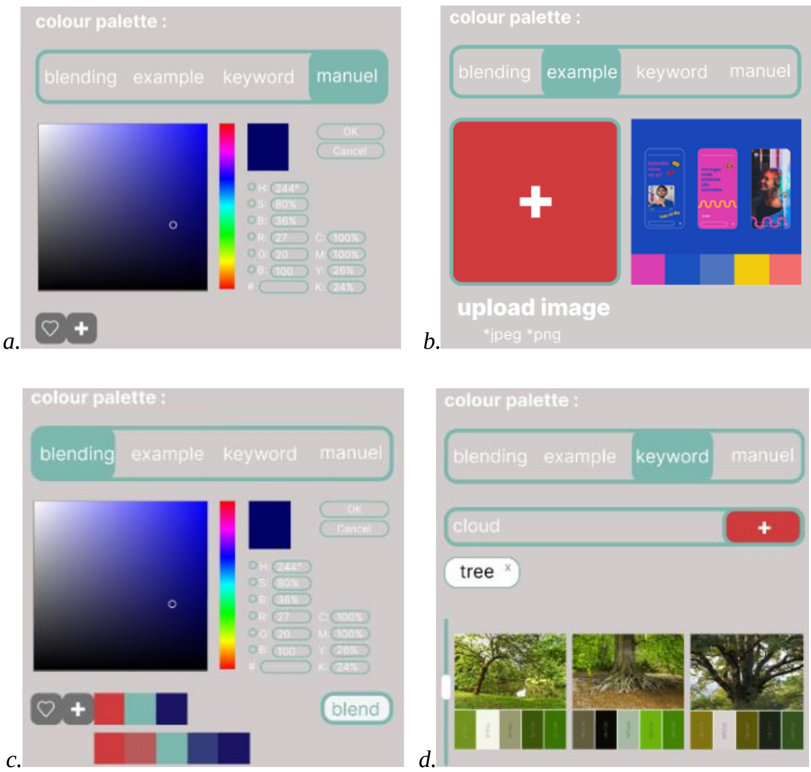

Figure 3. Color palette creating options *a.*manual option that allows user to choose colors via a color picker *b.*example option that extracts a color palette from an uploaded image *c.*blending option that creates new shades from selected colors *d.*keyword option that generates a color palette from input text

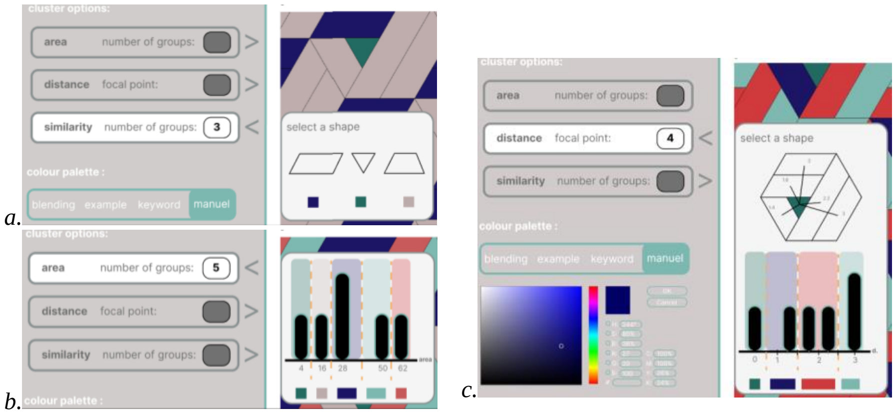

Figure 4. Shape clustering options *a.*cluster by similarity, based on the number of groups *b.*cluster by area, based on the number of groups *c.*cluster by distance, based on the focal point of shape.

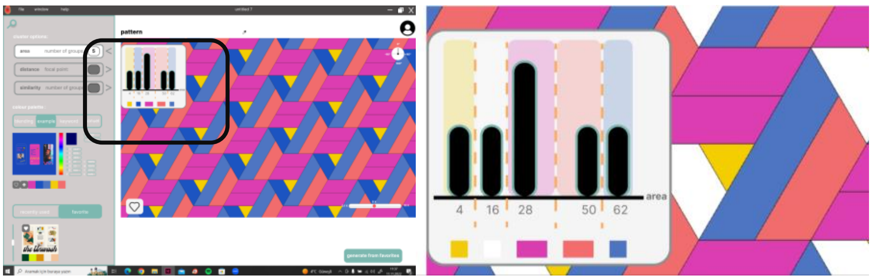

Figure 5. The Interactive histogram allows users to apply color changes dynamically on sub-shapes by distribution based on geometric features, e.g., size and distance.

Color artists have the option to save generated color palettes or compositions in a repository for future reuse (Figure 6). This allows them to generate new alternatives by combining the existing palettes within a new composition of patterns by selecting them from their favorites section (Figure 7). *ColorCraft* generates alternatives based on the preferred clustering and coloring options. Users explore different coloring combinations for constant clustered shapes or experiment with various clustering options for a selected color palette. Furthermore, users can share their favorite pattern compositions with their team or other relevant parties, facilitating collective contributions to the design evaluation process by ranking favorite alternatives (Figure 8). At the end of the process, users can view the average scores and sort the designs based on popularity, from most liked to least liked (Figure 9). To leverage the cloud system integrated into

ColorCraft, designers can add their designs to the repository and reuse them. They can also share their designs with their team. However, to ensure their designs remain within the system, designers are required to register an account.

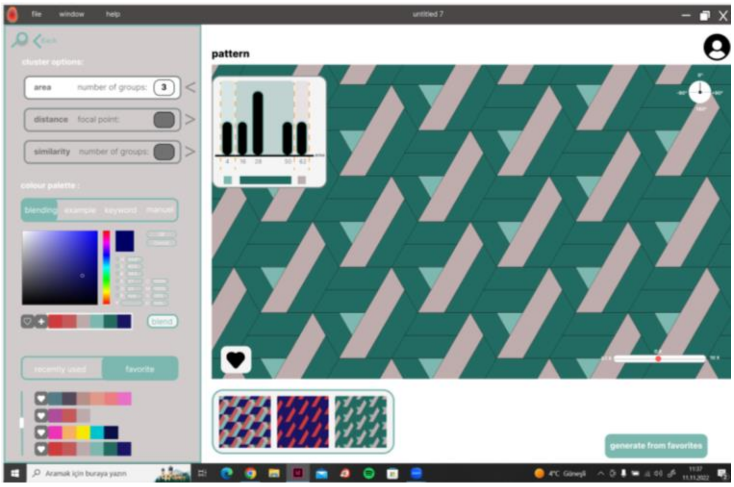

Figure 6. Saving colored pattern compositions to the repository.

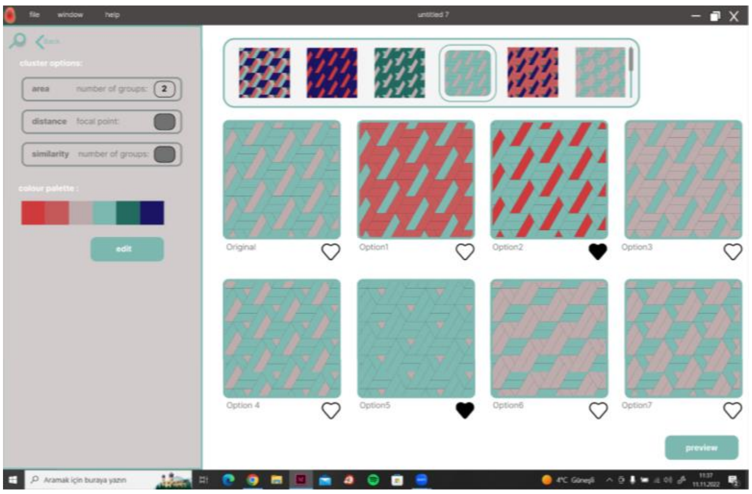

Figure 7. Generating new alternatives from favorite pattern compositions.

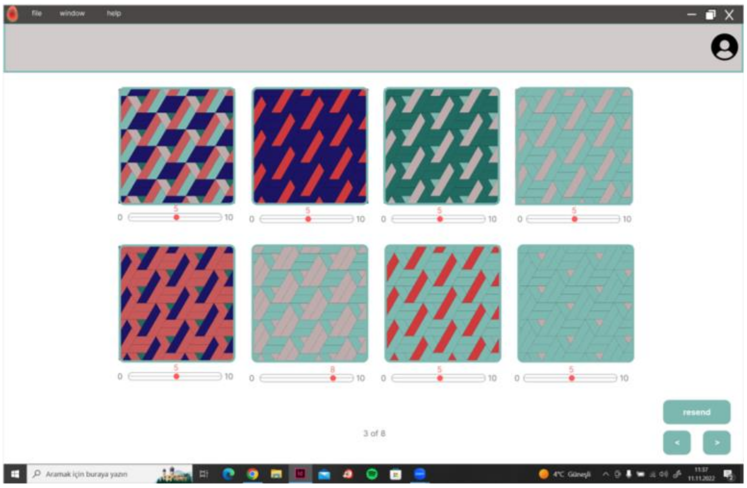

Figure 8. Ranking favorite designs within the team.

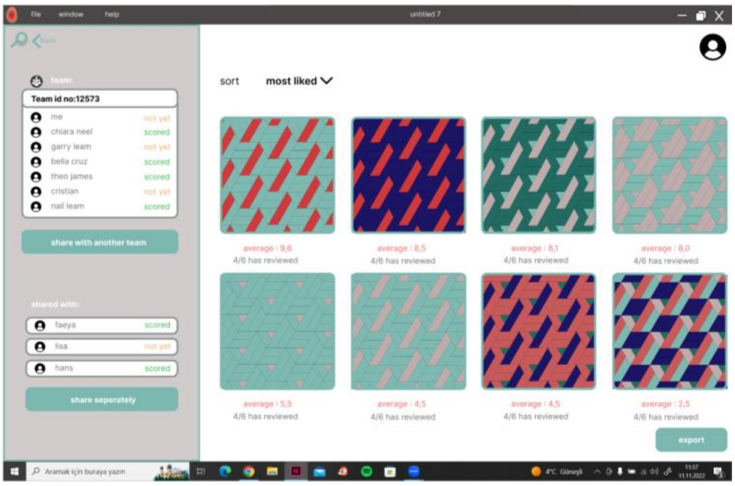

Figure 9. Sorting favorite designs according to average scores.

5.4. PATTERN PALETTE WITH CST PRINCIPLES

ColorCraft aims to facilitate creativity and enhance the exploration of different color combinations through iteration. By applying different color combinations to a pattern, users can perceive the pattern in many ways, supporting an ongoing and open-ended process of visual thinking through iterations. This aligns with Shneiderman et al.'s (2005) proposition for encouraging users to experiment with materials, explore multiple alternatives, change directions during the process, deconstruct and reconstruct, and create new versions.

A crucial aspect of creativity is the ability to explore numerous alternatives. Creative work often involves an unknown final design, requiring users to actively explore the design space (Fischer, 1994) and unlock its discovery potential. In this context, *ColorCraft*, provides a process for searching for meaning and engaging in visual reasoning. Decomposing elements with different coloring allows users to experience this exploration. Additionally, the compare and evaluation section of *ColorCraft* supports the exploration of different alternatives based on the most liked patterns, further enriching the design process.

ColorCraft enables the creation of an infinite variety of geometric patterns. While the selected base pattern remains constant, the clustering options generate indefinite visual elements. Pairing geometric patterns with colors adds a playful dimension to the creative experience. The interactive editing feature, including the histogram, enhances the user's ability to manipulate and refine their designs. This creative experience is in line with the discipline of "support exploration."

As technology-based products become increasingly complex, it is a common misconception that more features or settings make a tool more efficient and useful (Shneiderman et al., 2005). However, prioritizing simplicity and user accessibility is crucial. In line with this understanding, *ColorCraft* is designed to consist of two main parts: coloring and clustering. These are the only inputs required from users, and they are placed close to each other on the same page to minimize confusion and unnecessary navigation. Page changes occur only when switching between functions such as editing and evaluating, with clear buttons providing hints about upcoming actions. This design approach aims to reduce users' cognitive load and enhance program usability.

6. Evaluation

6.1. FOCUS GROUP RESULTS

The focus group aimed to assess the usability, user experience, and creativity support of *ColorCraft*. The following are the key findings from the evaluation:

During the focus group, participants found the pattern coloring features easy to use and follow. They expressed the benefits of instant visibility of changes and the ease of making color adjustments. Comparing and selecting patterns found clear and the histogram interaction well designed. The size of the window for favorites and histogram was satisfactory, although some reviewers suggested the histogram be resized, reconfigured, or repositioned.

Users found *ColorCraft'*s features intuitive and friendly, requiring minimal mental effort. Previews of colored patterns are seen as useful, especially when the exploration processes take a long time. Adding colored patterns to favorites and generating new patterns among them in the compare section was not bothersome, and the distinction between designs, compare, and evaluation features was clear. Exploring designs in the compare section was effective, and the fluidity of clustering and coloring options was praised, though some designers prefer a step-by-step process. The UI design was distinguishable, but separating clustering and coloring visually was suggested. Extra marks like undo/redo buttons and a navigation section are requested. Due to the space limitation, we preferred to exclude the experts' quotes.

The evaluation of *ColorCraft* highlights its potential to improve coloring applications across various design domains, including graphics design, architecture, and interface design. The positive reception and constructive suggestions provided by the artists who participated in the evaluation process reinforce the importance of developing tools that augment the creative exploration of pattern coloring. By addressing the challenges posed by generative design tools, which often impose limitations on designers such as mental effort, narrow templates, restricted options, and recognizing the limitations of manual coloring tools in terms of providing alternatives, this study contributes to the understanding of a mixed-initiative system for effective tool development. We aim to develop a deeper understanding of how these systems can support and enhance designers' creativity, ultimately improving the overall design process.

The evaluation provides significant insights that hold implications for the development of a new system for coloring artists. One of the key findings indicates that the design view and different coloring UX techniques reduce mental effort while increasing user-friendliness and accessibility. Participants appreciated the flow in clustering and experimenting with color compositions. They also desired more guided support and visually separated sections. Their interaction with the prototype was limited due to a lack of "back to the previous state" features, such as Undo or Redo. The interactive editing features, including the histogram, improve the manipulation and refinement of designs. Especially, the histogram received positive feedback as contributing to a seamless coloring experience.

The compare and evaluation views were found useful for enabling the exploration of alternative patterns considering user preferences. Continuous visibility of generated designs on this view enhanced the exploration process. The dependency on adding patterns to favorites to generate new pattern colorings in the compare part was not limiting for most users nevertheless participants suggested a "review history" feature.

6.2. FINDINGS AND DISCUSSION

We observed four thematic findings or suggestions after analyzing the feedback we received: users and tasks, the effect of UI layout on cognition, multiple base patterns, and collaboration style. The topics discussed in these headings are explained in detail below.

6.2.1 Linear Process or Back and Forth Process May be a Preference of Different Types of Users

Different types of users prefer different ways of using *ColorCraft*. In the focus group, we observed that some designers were pleased with the linear process and others with the dynamic systems that enable going back and forth. It is discussed that what if the generating from favorite patterns feature added in the repository were in the design screen and the system can generate alternatives simultaneously with the designers' decisions while designing pattern colors. Although the idea can support the exploration process according to one participant in the case study, the other type of participants thought that it might be confusing. Therefore, instantly generating systems may not fit all designer types. In these types of situations, there can be an option that enables users to on/off the feature, so that they can modify *ColorCraft* based on their preferences.

6.2.2 Screen Layout Might Interrupt Design Process

ColorCraft divides the locus of attention based on the color-adjusting tasks and color application tasks to enhance coordination. The pattern preview options view and pop-up histogram window open on the pattern view. These pop-up windows were not appreciated by some types of users since they block a part of the pattern viewing screen. They mentioned that it interrupted their design processes. They commented that if the histogram view appears under the related setting, it might help coordinate the two views better. Another group of reviewers preferred seeing the histogram on the pattern but was able to move or relocate it.

6.2.3 Using Multiple Base Patterns Can Enhance Exploration

Designers commented that *ColorCraft* might support the creative exploration process better if they could have a chance to change the base pattern. It discussed that there might be multiple tabs that belong to different base patterns and if they could switch between tabs, they would have more options and alternatives simultaneously. However, the simplicity of the program could have been lost and it may harm user-friendliness. Therefore, being able to reach multiple patterns in a single project file is a controversial issue for multiple types of designers. In addition, it could have made the UI complicated.

6.2.4 Collaboration Style Should be Both Internal and External

ColorCraft supports various collaboration tasks and is appreciated by the users. For example, multiple designers can work on the same pattern coloring project and explore alternatives, they can share their designs with each other, and rank shared designs. Furthermore, the program should also support digital communication since the users need to comment on and add notes on the designs. It is discussed that the decisions related to collaboration and communication should be tested with a variety of teams. It is important to support many types of collaboration for diverse backgrounds and experiences.

7. Conclusion

We presented a system study combining color generation and application for pattern coloring and an early UI prototype called *ColorCraft*. It is a mixed-initiative co-creation system designed to support artists in generating, using, and exploring color schemes for a variety of visual patterns. We demonstrated UX features on *ColorCraft* for generative coloring and manual coloring of patterns. *ColorCraft* follows the creativity support tool principles (Shneiderman et al., 2005) to empower artists to explore alternatives in applying colors to patterns and enhance their creative process.

These findings provide insights into the system's usability, highlighting areas of satisfaction and potential improvements. Furthermore, the study aimed to provide a fresh perspective and deepen understanding of how a mixed-initiative system should be designed, taking into account artist involvement, interaction, and support for their creative process. This approach aims to minimize the disadvantages often associated with generative tools, thus enhancing the overall experience for artists.

Acknowledgements

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We used ChatGPT (OpenAI, 2023) for editing grammar with the following prompt "*Could you edit the following text's grammar for an academic conference publication*?". We changed the text edited to tone the language.

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BEYOND PHYSICALITY

Exploring the Aesthetic Relationship Between Personality and Space

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Abstract. In his seminal work "the poetics of Space", Gaston Bachelard explored how space shapes our perceptions of the world. Personal space is a vital aspect of this discussion as it not only influences our behavior but also reflects our personality. The formation of personal space can be a manifestation of our identity, and therefore, understanding its correlation with personality is crucial. The present study focuses on assessing and comparing different personal spaces, specifically bedrooms, by analyzing their spatial arrangement and characteristics. To achieve this, the study employs photogrammetry to scan the bedrooms and create 3D point clouds for analysis. The aesthetic outcome of this research is a digital symbiosis of these 3D scanned bedrooms, which reveals the connections among them. By examining personal spaces through a scientific lens, we hope to deepen our understanding of how the physical environment reflects our inner selves.

Keywords: *Photogrammetry, Point-clouds, Immersive Data Visualization, Machine Learning, Environmental psychology.*

ملخص. في عمله المبدع "شاعرية الفراغ"، اكتشف غاستون باشلار كيف يشكل الفراغ تصوراتنا للعالم. تعد المساحة الشخصية جانبًا حيويًا في هذه المناقشة لأنها لا تؤثر على سلوكنا فحسب، بل تعكس أيضًا شخصيتنا. يمكن أن يكون تكوين المساحة الشخصية مظهرًا لهويتنا، وبالتالي فإن فهم ارتباطها بالشخصية أمر بالغ الأهمية. تركز الدراسة الحالية على تقييم ومقارنة المساحات الشخصية المختلفة، وتحديداً غرف النوم، من خلال تحليل ترتيبها المكاني وخصائصها. ولتحقيق ذلك، تستخدم الدراسة التصوير المساحي لمسح غرف النوم وإنشاء سحب نقطية ثلاثية الأبعاد لتحليلها. النتيجة الجمالية لهذا البحث هي التعايش الرقمي بين غرف النوم الممسوحة ضوئيًا ثلاثي الأبعاد، مما يكشف عن الروابط فيما بينها. ومن خلال فحص المساحات الشخصية من خلال عدسة علمية، نأمل في تعميق فهمنا لكيفية انعكاس البيئة المادية على ذواتنا الداخلية.

الكلمات المفتاحية: *التصوير المساحى، سحب نقطية، تمثيل البيانات الغامر، التعليم الآلى، علم النفس البيئى.*

1. Introduction

Space, in its various forms, has long been recognized as a powerful influence on human perception and experience. Gaston Bachelard, in his seminal work "The Poetics of Space," delved into the profound relationship between space and our understanding of the world around us (Bachelard, 2014). Among the many dimensions of space, personal space stands out as an essential aspect that not only shapes our behavior but also acts as a reflection of our individuality. The configuration and characteristics of personal space, particularly within the context of bedrooms, can provide valuable insights into the personalities of their inhabitants (Gosling et al., 2002). Exploring the correlation between personal space and personality could assist in unraveling the complexities of human identity.

The investigation of personal space is an interdisciplinary pursuit, merging principles from psychology, sociology, and environmental studies. Psychology and neuroscience have emerged in recent years as subjects of interest for the computational design in the architecture community (Horvath, 2022). Delving into personal spaces allows us to uncover how the external surroundings mirror the inner identities of people. (Bachelard, 2014) has described how personal space is not solely a physical construct but also carries emotional and symbolic significance. Our study seeks to contribute to this statement by employing a Machine Learning (ML) data visualization technique to analyze and interpret the spatial characteristics of bedrooms, more specifically colors, shapes, and size.

The present study aims to assess and compare different personal spaces, focusing specifically on bedrooms, through an analysis of their spatial arrangement and distinctive features. By employing advanced photogrammetry methods, we will capture detailed three-dimensional (3D) point clouds of these bedrooms, enabling a comprehensive investigation of their spatial qualities. Furthermore, the aesthetic outcome of this research will be a digital symbiosis—a visual representation of the 3D scanned bedrooms—revealing the intricate relationships between the various personal spaces.

By delving into the realm of space through this method, we hope to deepen our comprehension of how our physical surroundings may reflect our character. The findings of this study hold implications for various fields, including Environmental Psychology (EP), Architecture, and spatial data visualization. Furthermore, they may contribute to the development of personalized and emotionally resonant spaces that cater to individuals' unique needs and aspirations. This can be achieved by the categorization of the

personalities and their aesthetic preferences, and therefore, provide insights from references.
In the subsequent sections, we will delve into the methodology employed for capturing and analyzing personal spaces, present the results of our investigations, and discuss the implications and potential applications of this research. By merging the insights gained from the spatial analysis of bedrooms with our understanding of human psychology and personality, we aim to provide a framework to further explore and, therefore, attempt to understand the intricate relationship between personal space and identity.

2. Background and Literature Review

The phenomenon of place, space as a medium, and data visualization are central themes in the exploration we forged to understand personal space. Place holds a profound influence on human experiences, encompassing the emotional, cultural, and social dimensions of an environment.

2.1. THE PHENOMENON OF PLACE

The notion of place holds profound significance as it embodies a fundamental expression of human engagement with the surrounding world. Understanding the essence of places is not only crucial for creating new environments but also for preserving and renewing existing ones (Relph, 2007). Wagner (1972) eloquently captures the inseparable unity of place, person, time, and act, emphasizing that to truly be oneself, one must occupy a defined space and engage in meaningful actions. However, grasping the elusive concepts and attributes of places remains challenging, as they cannot be rigidly defined. To address this, Hugh Prince advocates capturing the "essential character" or fundamental nature of places (Prince, 1962).
Environmental psychology emerges as a field that systematically explores this "essential character" of spaces. Integrating various disciplines such as anthropology, architecture, planning, psychology, and sociology, EP examines and records the intricate relationship between humans and their environment (Bechtel, 2010). The human-environment relationship is symbiotic, with both elements continuously interacting and influencing each other. While fundamental laws describe the physical environment, human perception varies individually and culturally.
People's place identity and the identity of a place are interconnected yet distinct concepts (Proshansky, 1983). Both encompass emotional bonds between individuals and their physical surroundings. People's place identity, an integral part of their personalities, is shaped by significant locales that contribute to forming their sense of self (Lewicka, 2011). On the other hand,

a place's identity embodies the distinctive character attributed to it, often by its inhabitants (Relph, 1976). This reciprocal interaction between people and place leads to the shaping of both social and personal identities (Nario-Redmond et al., 2004).

Individuals not only contribute to but also construct the identity of a place, drawing from a range of physical, symbolic, and institutional components (Raagmaa, 2002). This identity, reflected through people's consciousness, originates from various facets of the place and is generated primarily by the human nervous system (Stokols, 1996). Alterations in these components, whether triggered by external forces such as natural disasters or globalization, or by internal processes like regional development, can profoundly impact the identity of a place and the corresponding place identities of its inhabitants (Hernandez et al., 2007). Even the sounds that exist in a space at different times can change its character and how it is perceived by those interacting with it (Eskildsen & Horvath, 2022).

This mutual, dynamic, and ongoing interaction between individuals and their environment underscores the creation and cultivation of place identity as a circular process (Ramos et al., 2016), see Fig. 1. As individuals contribute to the identity of a place, they also draw from and are influenced by it, leading to an intertwined relationship that continuously evolves over time (Relph, 1976; Guiliani & Feldman, 1993). Thus, the development of place identity is a multifaceted endeavor where individuals and their surroundings coalesce to create a complex and enduring bond (Gustafson, 2001).

Bachelard's perspective on houses underscores the idea that every house is a geometrical object, but it can also house human complexity and idiosyncrasy if it aligns with its inhabitants. He views the house as a haven for dreaming and self-expression (Bachelard, 2014). Personal environments, such as bedrooms, hold significant meaning as individuals spend much time there, repeatedly performing certain behaviors that leave discernible residues (WEBB et al., 1966). George Perek's description of his bedroom belongings as his "fortune" reveals the profound connection between individuals and the objects in their rooms, which become key points in narrating their lives (Perec, 1997).

The project begins with the assumption that bedrooms reflect individuals' identities through the personalization and arrangement of space, whether consciously or unconsciously (Gosling et al., 2002). Steinbeck's observation (1962) reinforces the idea that one can learn much about individuals from the spaces they inhabit. Environmental elements act as lenses through which observers indirectly perceive underlying constructs (Brunswick, 1956). Personal environments serve as repositories of individual expression from which observers draw inferences about the occupants, linking occupants to their environments through various mechanisms (Gosling, 2002).

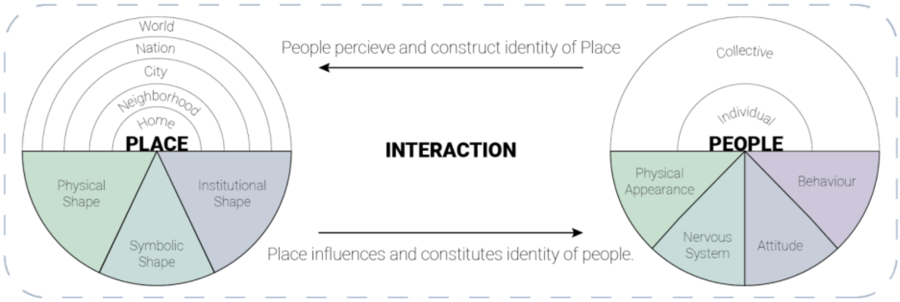

Figure 1. Relationships between people, place, and place identity, as redrawn from (Peng et al, 2020).

2.1.1 GENIUS LOCI

Norberg-Schulz (1979) asserted that a place serves as a unifying force, binding a group of people together, fostering a shared identity, and nurturing social relationships, friendships, and communal bonds. This concept of place was subsequently incorporated into the architectural field, leading to the emergence of the theory of genius loci (Norberg-Schulz, 1979). Langer (2001) further contends that place extends beyond a mere abstract location, encompassing a profound and multifaceted significance.

While the concept of Genius Locci originally emerged from the understanding of the spirit or essence of a place in the context of outdoor environments, it can also be extended to encompass indoor spaces where individuals spend a significant amount of time. In the case of a bedroom, the genius loci can be perceived through the unique and personal characteristics of the space. Each bedroom reflects the preferences, personalities, and experiences of its occupant. The arrangement of furniture, the choice of colours and decor, the personal belongings, and the overall ambience contribute to the distinct essence of the bedroom. This intangible essence arises from both the tangible aspects that are observable and touchable, and the non-material elements tied to emotions, memories, and personal associations with the space.

Genius loci, as conceptualized by Norberg-Schulz, exhibit certain affinities with the ideas of self-organization due to their emergent and dynamic nature. Self-organization refers to the process by which complex systems spontaneously form and evolve, resulting from local interactions among their components without any central control (Sneyd, 2001). Similarly, genius loci are not artificially created but emerge organically from the interactions between people and their environment, encompassing both tangible and intangible elements.

2.2. THE MEDIUM OF PERSONAL SPACE

Marshall McLuhan's statement, "the medium is an extension of man," (McLuhan, 1994) aligns with Bachelard's exploration, emphasizing that personal spaces, such as bedrooms, serve as mediums that extend and shape our inner selves. In the context of this present study, personal spaces can potentially act as expressive mediums, and embody the complexities of individual personalities. This study utilizes photogrammetry to assess and compare different bedrooms, recognizing it as a medium that captures some aspects of the multilayered essence of individuals. By bridging the physical and psychological realms, we aim to reveal the interplay between our inner selves and our surroundings. Photogrammetry facilitates the digitization of physical objects encompassing factors such as position, orientation, shape, and size (De Paolis et al., 2020), an example of a 3D scanned bedroom can be seen in Fig. 2.

Figure 2. An example of a dense point cloud. A digital space replica of the rooms scanned for this project.

2.3. THE AESTHETIC AND CULTURAL DIMENSION OF DATA VISUALIZATIONS

Data visualization serves as a cognitive enhancer, facilitating comprehension of the intricacies inherent in high-dimensional data sets and patterns (Lunterova, 2019). Over the last decades, 3D data visualization has emerged as a vast subfield of computational design for architecture, with examples ranging from simple renderings of designs to enhanced VR experiences

(Horvath et al., 2021), all in recognition of the multi-dimensional data that accompanies the design and use of space (Vite et al., 2021). The human capacity to process vast amounts of raw data, particularly in representational formats like photogrammetry, is limited, especially when dealing with extensive 3D data, which can overwhelm perception and understanding due to its high dimensionality. However, data visualization transcends this limitation by employing dimensionality reduction techniques to convert data into graphical representations, enabling easier identification of trends, patterns, and relationships within the information. Integrating data visualization and machine learning, with dimensionality reduction, assists in unlocking hidden insights, enhancing decision-making and design processes, and achieving a deeper understanding of the characteristics and functionalities of living spaces in the multidimensional realm (Cantamessa et al., 2020).

In datasets characterized by high dimensions, such as photogrammetric representations of surrounding environments, each data point is represented by a multitude of features or attributes. However, not all of these features may possess significant relevance or contribute substantially to the overall information inherent in the data.

Two principal approaches stand out: feature selection and feature extraction (Liu & Motoda, 2012). Feature selection entails the deliberate selection of a subset of original features, driven by statistical measures, domain knowledge, or correlation analysis, leading to the elimination of irrelevant or redundant features. This process serves to simplify the dataset and enhance computational efficiency (Billeskov, 2018). Conversely, feature extraction involves transforming the original features into a novel set of lower-dimensional representations, adept at capturing essential patterns and variations present in the data.

The fundamental objective of dimensionality reduction is to identify a lower-dimensional representation of the data that retains essential information while alleviating the challenges associated with high-dimensional spaces, commonly known as the "curse of dimensionality." (Bellman, 1961) which describes the challenges and complexities associated with datasets with many features. This technique offers notable advantages, encompassing improved computation efficiency, elimination of redundant data, prevention of overfitting in machine learning models, and facilitation of more effective data visualization (Van Der Maaten, 2008).

However, the application of dimensionality reduction must be carefully considered, as well as the specific characteristics of the data and the analysis objectives. It is important to acknowledge that while dimensionality reduction can yield significant benefits, it may also result in some loss of information. Consequently, striking a balance between data complexity and simplification becomes a crucial consideration in employing this technique effectively (Lunterova, 2022).

3. Methodology

The research involved the participation of 20 individuals, all aged between 25 and 35 years, residing within the greater area of Copenhagen. Each participant occupies a shared apartment, wherein their bedrooms serve as repositories for their personal belongings. Consequently, these bedrooms emerge as the most pertinent and representative samples to glean insights into the lifestyles and personalities of the tenants.

The procedure is structured into three sequential steps. Initially, comprehensive documentation of the participants' bedrooms is undertaken, achieved through the capture of digital photographs of the spaces. Subsequently, the acquired images are processed in generating point clouds from close-range photogrammetric data. As a result, a 3D representation of each bedroom is formed, represented by a point cloud, which is then exported in .ply format. The aforementioned process is replicated for all 20 bedrooms to ensure a sufficient dataset.

The second phase involves the processing and conditioning of the amassed point cloud data. Data processing consists of three key stages: Preprocessing involves refining and structuring raw data. Main processing applies advanced algorithms and analytical methods to extract insights. Finally, post-processing visualizes the processed data for clearer interpretation and communication of findings. The first stage involves reading the point cloud data and extracting the corresponding (x, y, z) coordinates and color (RGB) information of each room. To standardize the point cloud data and facilitate comparative analysis, a command is executed to identify the bedroom with the highest number of points, and a padding method is employed to augment the point clouds of the remaining bedrooms by adding mean values. The t-distributed Stochastic Neighbor Embedding (t-SNE) algorithm (Van der Maaten & Hinton, 2008) is subsequently employed to compare the bedrooms with one another and reveal underlying patterns.

t-SNE, an unsupervised learning technique and powerful data visualization tool, is specifically suited for projecting high-dimensional data into a lower-dimensional space. The t-SNE algorithm in this study is configured with specific parameters, including "n components" set to 3, determining the desired dimension of the embedded space, and a "learning rate" of 200, optimized to prevent distortions in representation within the recommended range. Notably, the "perplexity" parameter is set to 3.0, even though the standard range lies between 5.0 and 50.0, a decision made due to the size of the dataset. These parameter selections are thoughtfully chosen to ensure the robustness and meaningfulness of the t-SNE visualization, enabling an insightful exploration of the relationships between the 3D scanned bedrooms and the personalities of their occupants.

3.1. DATA VISUALIZATION

To visualize the material qualities of places and uncover potential similarities between them, we propose utilizing an algorithmic approach. This endeavor seeks to capture the intangible essence inherent in physical spaces, which can be perceived through both sensory and spiritual experiences. The phenomenon of genius loci, comprising visible and tangible attributes alongside non-material elements, forms the foundation for this visualization effort.

By subjecting diverse places to analysis through the algorithm, we aim to discern patterns and commonalities among them, thus revealing underlying processes that contribute. This unique essence cannot be artificially fabricated, underscoring its inherent nature and role as a mediator and medium of social interactions within specific contexts.

In addition to identifying similarities, the application of the algorithm provides an opportunity to explore the threefold process that characterizes and preserves the essence of genius loci. This process entails an examination of underlying patterns, an analysis of related processes, and a nuanced understanding of the interplay between these hard and soft values.

In order to enable effective data visualization, we generated two scatterplots that depict the rooms as individual data points on both 2D and 3D axes. Each data point is labeled with the corresponding room owner's name and distinguished by a unique color. To provide a more comprehensive representation of the findings, two additional scatter plots were produced, wherein the data points (bedrooms) were substituted with thumbnails of the respective rooms.

Additionally, in order to enhance the expressiveness of the results, we also aimed to provide a comprehensive and engaging visual representation of the research findings, thus improving the dissemination of research findings to a broader audience. We developed an application to display all 20 point-cloud-based bedroom representations. In this application, the 3D scatterplot points were replaced with unified point clouds representing each room. To ensure user-friendly interaction, we included an instruction screen within the application to aid navigation, which can be seen in Fig. 3. We employed various tools to create this interactive visualization. Unity (Unity Technologies, 2019), a game engine, served as the primary platform. Additionally, we utilized PCX, a LiDAR point cloud data importer created by Takahashi (2017). To facilitate visual scripting, we employed PlayMaker (Hutong Games, 2017), a Unity add-on that utilizes functional state machines (FSMs).

Figure 3. The instructions panel was created to help the user explore the data, meaning the bedrooms and their connections.

4. Results

The findings of this research offer compelling insights into the intricate relationship between personal spaces. Through the innovative use of 3D scanning and advanced data visualization techniques, we have uncovered patterns and connections among diverse personal spaces. The results are communicated through **a)** Orthographic representation and **b)** Immersive exploration.

4.1. ORTHOGRAPHIC REPRESENTATION

The results of this research are presented in the following 2D and 3D (fig. 4. a, b and fig. 5. a, b) scatterplots. Each point of the plot represents a room. Different colors and screenshots of the rooms were used for a better understanding of the correlations between the bedrooms. In the 3D scatter plot correlations between bedrooms are shown, as viewed from a 3D perspective, similarly to the 2D scatterplot. Distinguished clusters are formed between both light and dark color-based rooms, bigger and smaller-sized rooms, and more and less homogeneous rooms.

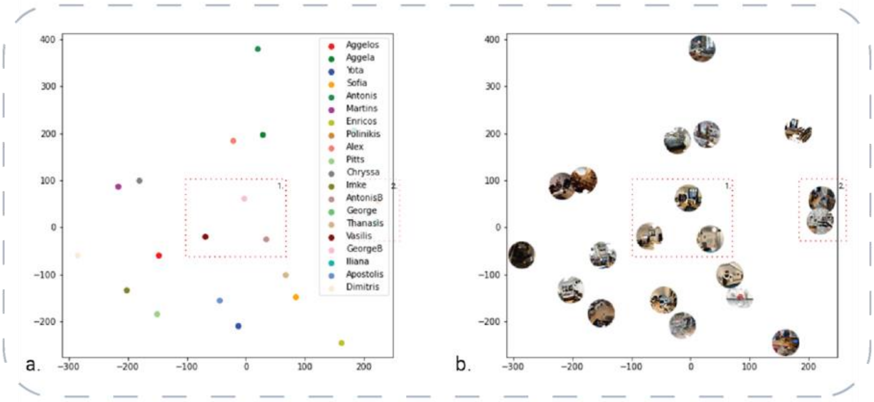

Figure 4. The Results of the t-SNE Analysis in 2D Scatterplot. a. The rooms are represented by coloured points. b. The rooms are represented by screenshots of the point clouds.

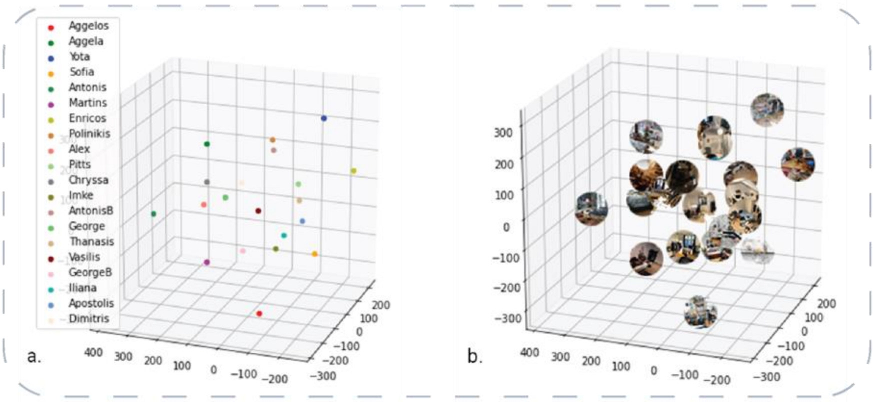

Figure 5. The Results of the t-SNE Analysis in 3D Scatterplot. a. The rooms are represented by coloured points. b. The rooms are represented by screenshots of the point clouds.

In Fig. 6, we can see Vasilis, GeorgeB, and AntonisB rooms that are forming a distinctive three-point cluster with beige-coloured rooms. These participants self-identify as males, hailing from Greece, and at the time of the research, their ages were 30, 28, and 27 years old, with two of them being flatmates. A notable pattern emerges as the dark color-based rooms tend to appear closer to the edges of the graphical representation, while multi-coloured and bright rooms are predominantly positioned in the center.

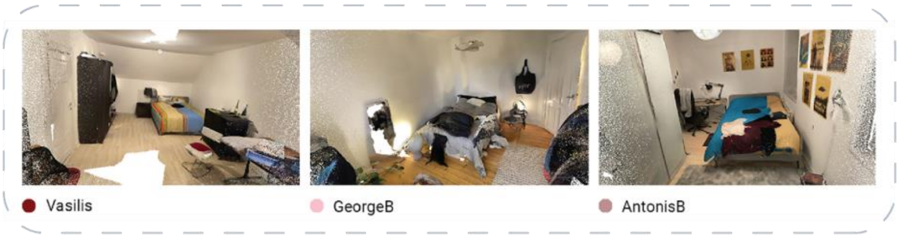

Figure 6. A closer look into one of the clusters that have been created. The cluster is marked in the histogram above (fig 3a.1), and (fig 4b.1)

4.2. IMMERSIVE EXPLORATION

Furthermore, we present below in Fig. 7 several screenshots of the application, providing an illustrative glimpse into the user experience it offers. Within the application, every point on the 3D axis is ingeniously substituted with the intricate point cloud representation of each distinct room. By seamlessly connecting these personal spaces in a cohesive 3D visualization, a digital symbiosis is created, enabling users to discern meaningful correlations and associations among the bedrooms and their respective owners. Users are granted the ability to traverse between various bedrooms, virtually immersing themselves in different personal spaces. This feature endows users with a unique sensation akin to soaring and exploring within the realms of diverse individual sanctuaries. The application facilitates an experiential journey through personal spaces, fostering a deeper connection between users and the data as they traverse the multifaceted landscapes of the 3D scatterplot.

Figure 7. The t-SNE Analysis results as experienced through the Unity-based application.

5. Discussion

The findings of this study resonate with the enduring perspective of Gaston Bachelard, who viewed personal spaces not merely as physical entities but as vessels of emotional and symbolic meaning. It contributes to on-going discussions on possible uses of machine learning for architectural design (Rhee et al., 2023, Pouliou et al., 2023). Leveraging advanced methodologies, including 3D scanning, machine learning and data visualization, we have empirically affirmed that personal spaces, exemplified by bedrooms in this study, are correlated with the character of their inhabitants. This validation enhances the domain of environmental psychology, reinforcing the profound interconnectedness of occupants between surrounding environments. In parallel, our investigation extends the concept of genius loci, traditionally associated with outdoor settings, into the realm of indoor spaces. The distinctive essence and attributes of personal spaces, as unveiled through our analysis, harmonize with the principles of self-organization, wherein these spaces dynamically extend the personas of their occupants. As a result of this interconnectedness, architectural and interior design practices are urged to pivot towards making spaces that are suited to each individual's personality and aspirations, in order to create a harmonious symbiosis between the inhabitants and the surroundings. The innovative fusion of photogrammetry, and machine learning data visualization as a means to dissect personal spaces presents a potential path for future interdisciplinary exploration. The techniques harnessed herein serve as potent tools for discerning latent patterns and intricate relationships from complex, high-dimensional datasets. The study thereby underscores the latent potential of data-driven methodologies to unveil concealed insights within intricate domains, analogous to the aims of experimental philosophy in questioning fundamental concepts.

5.1. METHODOLOGICAL CONSIDERATIONS & LIMITATIONS

While the methodology has unearthed valuable insights, it remains pertinent to acknowledge its limitations. The study's sample size, confined to 20 participants within a specific geographic scope, potentially constrains the representation of diverse personal spaces and identities across varied cultures and regions. Consequently, the transferability of our findings to a broader populace necessitates careful consideration. Moreover, the efficacy of the t-SNE algorithm, although proficient in dimensionality reduction and visualization, hinges upon meticulous parameter configuration. The selection of parameters, such as perplexity and learning rate, imparts a discernible influence on the visual representation and resultant clusters. The evolution of this research should encompass the exploration of alternative dimensionality reduction techniques or sensitivity analyses to buttress the robustness of outcomes.

5.2. FUTURE DIRECTIONS

Regarding the proposed method, we could analyze the rooms and extract their features before visualizing their correlations. This could be succeeded with the implementation of algorithms like pointnet (Qi et al., 2017). Furthermore, expanding the sample size to cover a more diverse cross-section of cultures and geographies will provide a more comprehensive understanding of the interwoven dynamics between personal spaces and identity. Finally, the integration of qualitative methodologies, akin to experimental philosophy's penchant for delving into intangible concepts, offers a deeper insight into participants' perceptions and emotional entwinements with their personal spaces.

6. Conclusions

This study has delved into the intricate relationship between personal spaces, and their connection to human identity, shedding light on the complex interplay between spatial arrangement and individual personalities. As a medium that extends and shapes our inner selves, bedrooms reveal the characteristics and configuration that reflect their owners' individuality. Our research highlights the potential of modern tools and methodologies to further clarify the emotional and symbolic significance of personal space, just as Gaston Bachelard's "The Poetics of Space" revealed this significance.

The visualization of our findings, both in 2D and 3D scatterplots as well as through an immersive application, offers a novel and engaging approach to understanding the complex relationships between personal spaces. This methodology has allowed us to discern clusters and correlations among different types of bedrooms, revealing patterns that go beyond mere physical attributes. In conclusion, the purpose of this interdisciplinary approach is to provide a deeper understanding of how personal spaces serve as expressive mediums of human identity, by comparing them with each other. We acknowledge that this is an overarching aim, given the intricate nature of human individuality. The implications of this research extend beyond data analysis, affecting architects, designers, and urban planners as well. The techniques outlined here can be refined, allowing for tools that assist individuals in assessing and optimizing their personal spaces, thus enabling informed design decisions to be made, by reference.

Our study aims to amplify and empirically examine assertions regarding the nuanced interplay between human intuition and physical configuration, as well as to advance these assertions. By combining contemporary approaches with traditional concepts, we can gain a better understanding of how personal spaces are shaped and reflect individual identities.

Acknowledgements

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FLUENCY OF CREATIVE IDEAS IN THE DIGITAL AGE

Exploring emergent AI influences on design methodology and visual thinking in architectural education

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Abstract. Research has explored the concept of originality in visual thinking and architectural education, using different methods. The new state of Artificial Intelligence (AI) in architectural design represents another shift from traditional modes of architectural design and education, into a more authentic approach to the digital age. An experiment is designed to highlight the originality of this approach in design thinking and its futuristic trends and impact on education and creativity studies. The intent of the study we present here is twofold: one to revisit key design studies of design exploration and secondly to explore students' design activity while interacting with text-to-image diffusion machine learning (ML) generative models such as Midjourney, DALL-E and Stable Diffusion, as these might have the potential to change the way that architectural students approach the concept stages of designing projects and products. In addition, we are interested in how the new shift in interfaces and modes of stimulus will influence the students' design process and perceptions. Participants in the design process are final year students who had spent at least four years in a school of architecture and can be classified as semi-experienced designers. Further within the evaluation also lies a critique of the diffusion ML tools themselves as producers of architectonic images, rather than complete concepts for architecture that encapsulate spatial, formal, structural arrangements of elements.

Keywords: *Architectural design, design activity, Ai Aided design, conceptual phase, machine learning.*

ملخص. استكشف البحث مفهوم الأصالة في التفكير المرئي والتعليم المعماري باستخدام طرق مختلفة. الحالة الجديدة للذكاء الاصطناعي في التصميم المعماري تمثل تحولًا آخر من الأساليب التقليدية للتصميم المعماري والتعليم، إلى نهج أكثر أصالة للعصر الرقمي. تم تصميم تجربة لإبراز أصالة هذا النهج في التفكير التصميمي واتجاهاته المستقبلية وتأثيره على دراسات التعليم والإبداع. القصد من الدراسة التي نقدمها هنا هو شقين، أحدهما لإعادة النظر في دراسات التصميم الرئيسية لاستكشاف التصميم وثانيًا لاستكشاف نشاط تصميم الطلاب أثناء التفاعل مع نماذج التعلم الآلي لنشر النص إلى الصورة مثل Midjourney وDALL-E و Stable Diffusion، حيث قد يكون لهما القدرة على تغيير الطريقة التي يتعامل بها طلاب الهندسة المعمارية مع مراحل مفهوم تصميم المشاريع والمنتجات. بالإضافة إلى ذلك ، نحن مهتمون بكيفية تأثير التحول الجديد وأنماط التحفيز على عملية تصميم الطلاب. المشاركون في عملية التصميم هم طلاب السنة النهائية الذين أمضوا ما لا يقل عن أربع سنوات في مدرسة للهندسة المعمارية ويمكن تصنيفهم كمصممين شبه متمرسين. علاوة على ذلك، يوجد داخل التقييم أيضًا نقد لأدوات التعلم الآلى كمنتجين للصور المعمارية، بدلاً من المفاهيم الكاملة للعمارة التي تغلف الترتيبات المكانية والرسمية والهيكلية للعناصر.

الكلمات المفتاحية: *التصميم المعماري، نشاط التصميم، التصميم بمساعدة الذكاء الاصطناعي، المرحلة المفاهيمية، التعلم الآلي.*

1. Introduction

Architecture is different from other arts in that its products must be simultaneously aesthetically beautiful, structurally sound, and practical, as stated by Song, Ghaboussi, and Kwon (2016). Further, the relationship between architecture and visual thinking is profound, as both fields are deeply intertwined and rely heavily on visual communication, creativity, and spatial understanding. Visual thinking plays a critical role in the architectural design process, enabling architects to conceptualise, communicate, and develop their ideas.

Established literature (Salman 2011; Salman et. al. 2014) discusses how design thinking may vary using different types of mediums, as such variations go beyond the type of interface to include personal methods of integration and association between digital, and physical, 2D and 3D formats, and any other medium that assists the designer in concept (re)structuring and (re)interpretation. Hence, the combination and integration of tools, representations and design exploration could bridge some of the cognitive differences between the designers and between the qualities and characteristics of the mediums used. This variation has the potential to enhance creativity and originality in the design process (Salman et al 2014). By allowing architects (or semi expert designers) to easily experiment with different design options and iterations, medium variations can facilitate the exploration of more unconventional and innovative design solutions. Additionally, digitally automating the creation of variation and optionality can assist the designer-architect in crystalising the core concepts of a design idea (Dounas 2019).

The design situation depends on what the designer can see and understand. “What if?” is a simple question set by Schön (1991) to define the design process as follows: “*to experiment is to act in order to see what the action leads to*”. What if? is an essential question needed to carry out any kind of design problem solving task, within individual design processes, mediums and tools.

2. Design process in research

According to Hevner et al (2004) heuristic search techniques result in workable, excellent designs that may be used in the real world. A Generate/Test Cycle is how Simon (1996) characterises the nature of the design process (Figure 1).

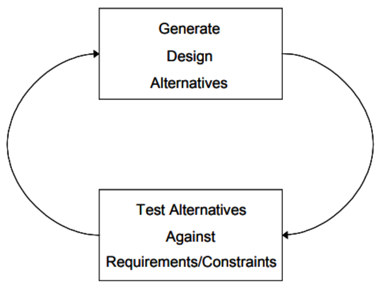

Figure 1. The Generate/Test Cycle (Hevner et al 2004).

Design is fundamentally a process of looking for a workable answer to a problem. Using available and accessible resources to achieve desired goals while adhering to design issues and constraints can be considered as problem solving (Simon 1996).

In design-science research, proper means, aims, and rules must be abstracted and represented. These elements always demand imagination and invention and rely on the problem and the surrounding environment. The collection of methods and materials that can be used to inspire and create a solution are called means. Ends serve as objectives and restrictions on the solution. Laws/ constraints are uncontrolled environmental factors (Hevner et. al. 2004). Knowledge of the solution domain, e.g., technical and organisational, as well as the application domain, e.g., requirements and constraints, is necessary for effective design. Drawing on Schön's (1991) question, the digital era could potentially reshape this notion: experimentation now becomes a means of stimulating curiosity, aimed at uncovering the pathways that prompts can unveil. Thus, envision a scenario where students acquire the skill of engaging AI-powered tools with prompts, thereby amplifying their imaginative faculties and exerting a deliberate impact on their creative capacities.

3. Exploration of visual thinking and design thinking methodologies

Visual thinking in digital mediums refers to the cognitive process of generating, processing, and communicating ideas, concepts, and information using visual elements within the context of digital technologies. In this context, visual thinking goes beyond traditional methods like text-based communication and taps into the inherent human ability to process and retain visual information more effectively. Digital tools (CAAD and BIM) enable individuals to create, manipulate, and share visual content in dynamic and interactive ways.

In examining the design process, external representations reveal the emergence of the design: these external representations are either verbal (words) or visual (graphic). This visual reconfiguration is considered as a phenomenon in other design studies, for example sudden insights (Restrepo and Christiaans 2004), discovery (Purcell and Gero 1998) and The Aha! response, or the sudden mental insight (Akin and Akin 1996) when a designer reaches an inflection point in the process that was not conceived or envisioned before. These studies emphasised the inductive role of the visual medium and its capabilities in containing (hosting) such emergence and the medium used in these studies was either 2D drawing or sketching.

In light of digital media studies, participants revealed that limiting the conceptual design medium would not always constrain them to a certain design strategy for the same design problem (or prompt) (Salman et al 2014).

3.1 STUDENTS SKILLS AND AGE GROUPS:

Subject review suggests that there are media-based differences among students in the design process. Younger students are using digital tools, and platforms quite naturally in the process as they tend to be more adventurous. This allowed the students to understand their own design better. Other studies (Al-Qawasmi's 2005) observed the same issue in substituting traditional methods with other methods and developing their design ability in a short time. Most of these studies (e.g. Hanna and Barber 2001; Dokonal and Knight

2006; Lu 2008) were carried out with students in their early stages of education. This suggests that an early-stage student is a better subject for studying attitudes and design media effect on thinking as they have no previous experience of CAAD, and no preconceptions or design habits that could bias the results. However, no study has focused on the acquired skills for the long-term teaching of digital tools in schools of architecture and whether the teaching methods used were appropriate or effective. It is, however, problematic to trace the development of design students' expertise (Dorst and Reymen 2004), whereby a longitudinal study is required to survey different cohorts within the same institution pedagogy.

Students with strong digital media skills are faster in production than other students, while the traditionally skilled students are able to reach a similar level to that of the digital group albeit at the sacrifice of longer production time. This study (Salman 2011) did highlight that during students' review, the reviewers (i.e., tutors) considered the images of the *digital models looked complete*. This impression was sometimes based on the appearance of the model (visualisation) only without the appraisal of the content, i.e., concept, relevance, quality of conceptual intrusions or viability. From the perspective of educators, it is suggested that using digital media alone in design exploration has advantages with some disadvantages.

In any case, the more manageable way is to focus on MArch students not only to identify their preconceptions but their reasons for having them, hence evaluating the efficacy of the teaching methods. This work, therefore, argues that any tool used to complement the visual thinking process will be perceived by each student differently, as this is influenced by the teaching methods and the teaching context.

3.2 STUDIES ON CAAD AND AI-AAD ROLE IN CREATIVE PROCESSES

The development of Computer-Aided Architectural Design (CAAD) and AI-Aided Design (AI-AAD) has shown some similarities, particularly in terms of technological rapid advancements and their impact on design processes, methodologies, and architectural education.

The noted similarities urged researchers in recent years to rethink CAAD to include its implicit relation to generative algorithms and architectural intelligence. However, architects have shown reluctance towards fully automated architecture generation despite the potential of generative algorithms. The issue of generating countless variations without meaningful outcomes is highlighted as unnecessary. Instead, architects prefer using digital tools that have evolved from CAD to BIM, allowing them to work symbolically with design elements (Stojanovski, T. et al. 2022).

Recent studies (Stojanovski, et. al. 2022) suggest future digital tools should incorporate AI to aid in human-computer interaction, design environments, and automating mundane design tasks, rather than generating entire designs. The role of AI (and any digital tool) should be to augment the design process, not replace it (Stojanovski, et. al. 2022; Salman et.al. 2014, Dounas. 2019).

The paper Stojanovski, et. al. 2022; acknowledges the ethical considerations surrounding digitisation, noting that technologies like AI can have both positive and negative societal impacts. The authors highlight the need to apply AI in ways that improve design processed, enhance design critical factors, such as sustainability, and benefit users in smart and intelligent ways. In general, we may state that research geared towards design **exploration** attempts, in a broad sense, to extend the solution space, producing a variety of models to aid the designer, and does not seek an exact answer (Castro Pena et al 2021). Additionally, utilising iterative methods and other AI techniques, should test and clarify the interplay of the many outputs involved in the design.

4. Overview of AI technologies relevant to architectural design

Presenting his insights, Daniel Bolojan (2022) articulates his conviction that artificial intelligence (AI), particularly image generation technologies, will exert a profound influence over the field of architecture. However, he advocates for a tempered approach to their utilisation, one that finds equilibrium through our comprehension and ongoing exploration of machine creativity. Bolojan's objective revolves around the creation of neural networks with the capacity to discern pertinent geometric principles, structural attributes, and compositional elements across diverse domains beyond architecture. He aims to achieve this by analysing examples encompassing Gaudí's Sagrada Família, as illustrated in the images below.

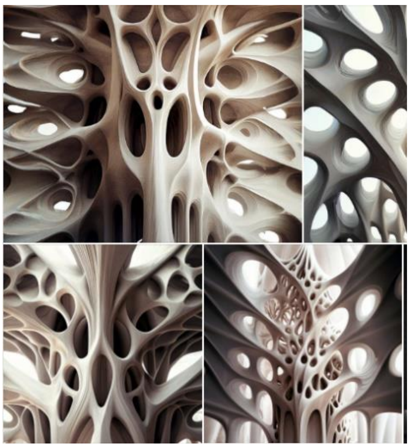

Figure 2. Nonstandardstudio, (2021). p.24, Machine Perceptions.

Bolojan's research (2021) highlights a significant transition from conventional expert systems, along with their design philosophy like parametric design, led to a transformation where the creative generative aspect of design has been somewhat overshadowed by a mere selection process. This evolution towards learning systems, however, is what Bolojan sees as the potential catalyst for a fresh surge of creativity.

Architect and writer Wolf D Prix (2022) explains the innovative path undertaken by him and his Coop Himmelb(l)au team. They have created a digital instrument named "The Legacy Sketch Machine" that harnesses algorithms grounded in their past architectural projects. This tool acts as a reservoir of concepts and resolutions, which it then transforms into sketches and illustrations. This serves as a valuable aid for architects during the design process. The authors are in the process of formulating the DeepHimmelb(l)au network, an ongoing endeavour. This network amalgamates components from diverse networks, including diffusion models, seamlessly fusing them to enable connectivity between different nodes. These nodes are tailored to specific design undertakings. The primary objective lies in optimising workflows through automation. However, they underscore that the ultimate aim is to enhance human intellect. An example is provided in Figure 3.

Figure 3. Coop Himmelb(l)au, DeepHimmelblau research project, 2021

5. Methodology

The design research and methods review established a "mixed methods" approach and two possible techniques for the purpose of this paper. The research timeline consisted of one experiment with two staged data; developing a workflow to explore students' perception and a follow-up questionnaire. This research method also can be coined as a structured reflection (Achten and Reymen 2005). The research objectives looked at

whether participants would comply with what was asked from them in terms of:
(1) the experiment guidelines, (2) the proposed design brief requirements and information/ absent information, and (3) the available Ai-AAD tools. In this case Midjourney was selected, due to the ease of set up and access by the researchers and subjects. Moreover, as part of this study's explorative nature, some of the research propositions were looked at through the derived data from literature review.

5.1 EXPERIMENT DESIGN

The sample was advanced year students, Master of Architecture, due to their perceived convergence of architectural expertise and technological aptitude. The selected sample is better equipped to identify and articulate potential problems or biases within the datasets. Additionally, their exposure to various digital architectural programs enables them to discern and provide commentary on workflow or underlying program issues as recognised in the study by Lyu et al (2022). All students were added to a Discord server that allowed them to create individual channels and allow direct manipulation of text prompts with Midjourney. The selected group of 9 students from stage 5 and 6 students was then randomly divided into two groups. Both groups were asked to develop 1 compelling concept image that they would be interested extrapolating, the image had to adhere to the brief which consist of the following requirements:

TABLE 1. Design brief to help with promoting

Location:	Isle of Uist, near LochMaddy Pier (Scotland)
Capacity:	up to 20 people
User types:	cyclists, families, walkers with pets, movement impaired
Functional:	Provide seating/leaning spaces, Open-air enclosed toilet/baby changing facility.
Weather protection:	shelter from winds and rain
Inspiration:	vernacular architecture of Uist and Hebrides
Materiality:	Focus on sustainability and environmental design- Reflect island's space race aspirations

Midjourney was selected for the workflow is Midjourney, as it “is an independent research lab exploring new mediums of thought and expanding the imaginative powers of the human species.” (Midjourney 2023). It is an interesting definition using the term "new mediums of thought", we may ask what is being elaborated upon. What exactly do these new media entail? Clearly defining these media would help educators grasp the tool’s focal points more effectively. The claim of "expanding the imaginative powers of the human species" raises questions about the practical implications of this expansion. How does the lab intend to measure and validate the enhancement of imaginative capabilities? Providing evidence or instances would lend authority to this ambitious objective.

5.1.1. The Workflow

The 4 students in Group 1 were instructed to use Midjourney with the specific workflow, shown in Figure 4, this was accompanied by a brief guide to writing prompts and selecting images for blending to create the most reliable estranged results. The control group, Group 2, made up of 5 students, used Midjourney freely without instruction outside of help accessing the software.

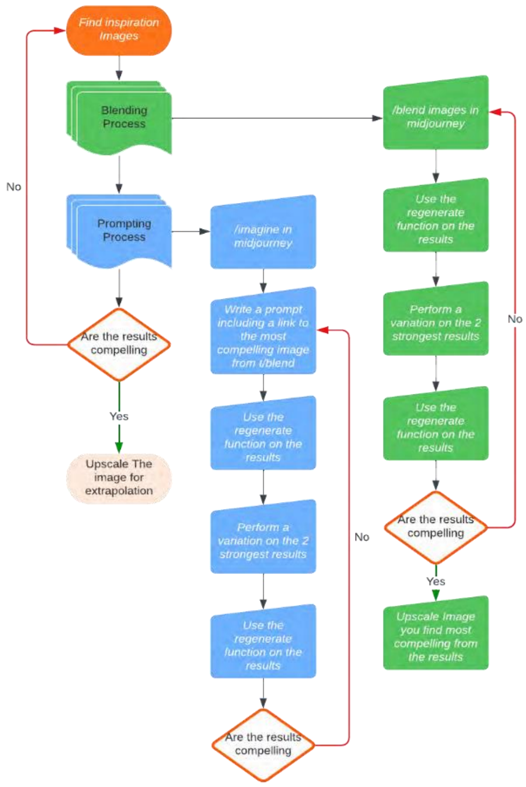

Figure 4. Midjourney Workflow flowchart (Clarke, 2023)

All the participants were asked to complete the task using no more than 5 attempts at a prompt. Each participant had access only to the information channels and a private Midjourney interface channels they do not interfere with the results of other participants/ the experiment.

The results were then shown to sixth year studio who were asked to pick the images they felt were the most compelling based on the following design criteria: creativity, relevance to the design brief, and quality.

The post experiment phase involved a questionnaire that included both qualitative and quantitative questions to gain a better understanding of how they perceived the technology, the proposed workflow and how productive it was.

5.2 FINDINGS

In the following sections, the results of the workflow testing, and the post experiment questionnaire are presented:

5.2.1. Workflow Testing Results

The findings from the peer review conducted by stage 6 students indicate that Midjourney's free use outperformed the traditional workflow across all aspects, as the three highest performing images all came from the control group. The base version of Midjourney produced more complete-looking images, the best-fitting image according to the brief was one where a user included a photo of Lochmaddy in the prompt.

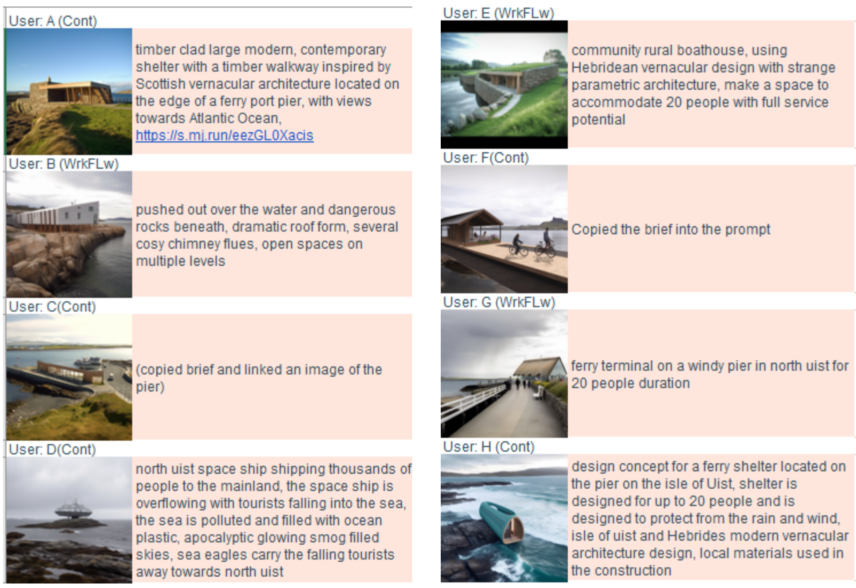

Figure 5. The results of the qualitative responses.

The choice of prompts and images, figure 5, had a significant effect on the output, as more experienced users performed better across the board. Unknowingly the experienced users were almost exclusively in the control group, though they had no experience with architectural application of Midjourney. Lastly users that generated clear, full view images of a structure from a logical perspective performed better.

The peer review favoured images that either tried to push the AI in a new direction or had a large amount of prior prompting experience. Those reviewing the images also favoured images that clearly represented Uist and the Outer Hebrides. This can be seen in the success of the results that included reference images in the prompts.

The best versions were achieved by users who either attempted to push Midjourney results in an unconventional direction or had significant prior experience with prompting, as shown in figure 4. Additionally, images that clearly represented Uist and the Outer Hebrides were favoured by reviewers, highlighting the effectiveness of including good reference images in prompts and confirming the basis for the workflow, even if the output requires work.

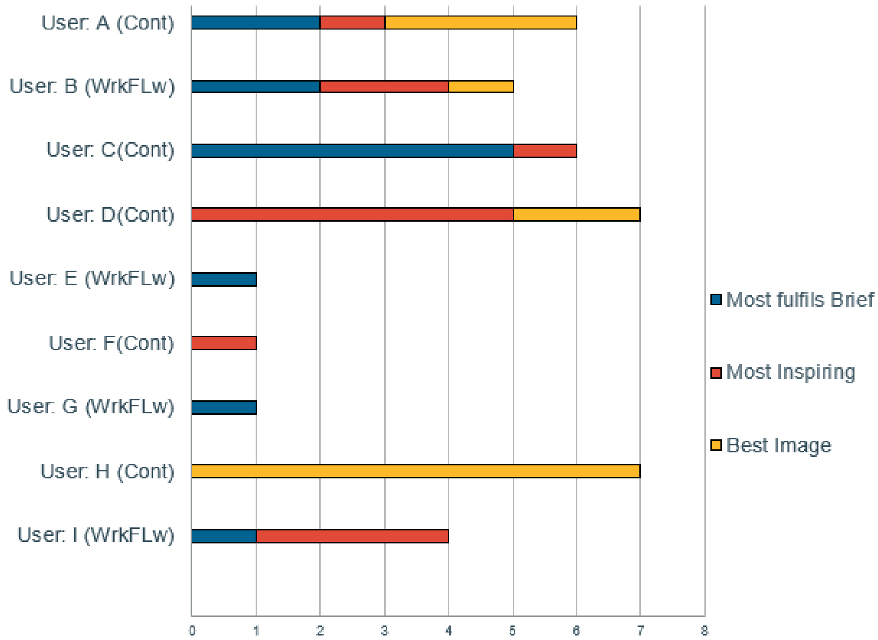

Figure 6. The results of the quantitative responses.

Midjourney free use was found to outperform the traditional workflow, with several factors contributing to these results. Existing barriers to using image generators include a lack of training or understanding of their usage.

Users found the experience with Midjourney informative and valuable, and gained a better understanding of the tool, viewing it as useful tools for idea generation and concept development as an augmenter and not an automator. Though users with the workflow found it supported them in their creativity more even if the results were perceived as less valuable.

Participants who had not used image generators before expressed interest in learning more and incorporating them into their workflows further all users see potential for the application of image generators in various fields in. Overall Midjourney was found to be a useful design tool and imagination augmenter by participants, their belief was that it would push them outside of their comfort zones, allow them to test new ideas, and allow them to design in a more contextually relevant way without resorting to imitation. Furthermore, an adjacent use was observed by participants, the creation of non-specific visual elements for use in renderings or other media, such as furniture, figures, or textures which could be expanded across similar creative and design fields.

5.2.2. Workflow Questionnaire Results:

Users that completed the workflow found the experience informative and valuable, suggesting that afterwards they had a much better understanding of Midjourney and how they thought about what they liked about the concepts presented that they could take forward to their own work. They also observed that there is clearly a lot of depth to explore with Midjourney such as what makes a good prompt or a good starting image for exploration.

Overwhelmingly participants found AI image generators to be useful tools for idea generation and concept development, either having their opinions changed or confirmed to this effect. The experiment helped some participants become more familiar with the AI technology and how to use it effectively in their design processes. As a result, 65% of users had not used the software for architecture and 50% hadn't used it at all, of that 65% the primary reason as a lack of familiarity, with one count of feeling it wasn't useful (shown in the figure below) however all of participants agreed after the experiment that the software had a potential in the field of architectural concept development.

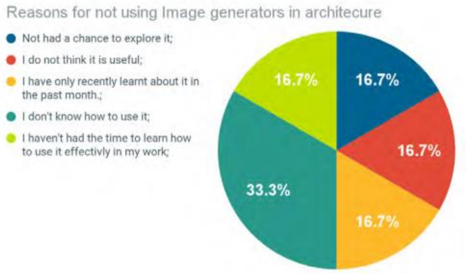

Fig 7. Questionnaire results (Clarke, 2023).

The majority of participants do not view AI as a replacement for human creativity and expertise, but rather as a complementary tool in the field of architecture, allowing them to question their own pre-held conceptions and preferences. Participants that had not used the software before and did not use the workflow expressed an interest in becoming more familiar with the techniques. Whereas the group that used the workflow felt that they were far more supported in their creativity than the control group, even though the control group had the higher number of familiar users. Though both groups felt equally likely to recommend Ai-AAD, showing that even some familiarity was all it took for users to see its strengths shown in the figure below.

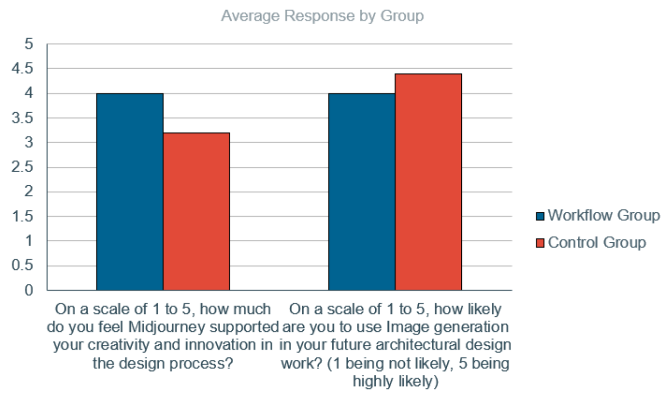

Fig 8: Questionnaire results (based on Clarke (2023) study).

Participants in Group one seemed to have a variety of different approaches to the task which runs counter to the purpose of the workflow but does prove the effect that the human component has, The students who were most successful in generating a final image opted for the more extreme approaches, Either doubling down on estranged components of the image or attempting to work through the abhorrent features to create something better the latter is not an approach that the experiment had envisioned.

The participants in group 2 (Control Group) that had not used image generators before most looked to experiment and learn as much as possible whilst trying to create a realistic design. Those who had used it before simply attempted to rapidly generate an image they felt was interesting using their own prior techniques.

Users in group 1 felt that they struggled to understand or predict outputs based on their prompts, this is perhaps more linked to experience than a fault in the workflow though could be a biproduct of seeking to create defamiliarization in the results. Two users also noted the tendency for Midjourney to become hung up on a single feature, this seems to be a habit of the new Version 5 that was not as common in Version 4 which provided greater diversity when using the variation command.

Overall, the more experienced members of group 2 did not notice any problems with using it in architecture however those that had not struggled to get it to understand which prompts where being waited in the result and why, one user also experienced one of the inherent risks in a remotely host third party neural network in that the service simply went down unexpectedly. All the participants believe that "Image Generators" will be the next step in concept generation in Architecture, however two expressed the opinion that the technology is not good enough yet. Users with no experience expressed an interest in becoming more informed on the software and its interface so as to be able to fit it into their own workflows in order to rapidly generate concepts for inspiration and exploration in a way vastly exceeding our historic means, most noted that the difficulty is knowing how to decide what is and is not valuable and when to stop ideating. Users that had experience but were not part of the workflow expressed a lack of ability to generate a predictable or deliberate outcome, and to emphasise its role as a tool and not something to be the sole source of your concept generation. Most also suggested a greater step by step guide would be required for training in prompting and blend image input choice.

6. Implications for Architectural Education:

The results of this study have implications for the wider field of architecture, design, and education as we examine what we think of as creativity and authorship when augmenting our imaginations with an artificial neural network-based technology.

Al-Qawasmi's (2005, 2004) study of the e-studio categorised students' practices in terms of using CAAD solely in the design studio, into enhanced practices and displaced practices. The enhanced practices were (1) integrative mode of working where the students' acts and decisions are saved in a digital construct or representation, (2) interactive mode of working where design manipulation is immediate (3) reflective through instant feedback, there is no time gap between the two, the immediate response to change is seen as a consequence rather than acting on the result through reflection, and (4) immersion felt in two modes, one of which was during projecting their models and navigating through their 3D models and the other was felt with the many choices of form generation. These effects reflect a 3D dominant mode of thinking and interactivity with design exploration. These have displaced other traditional based practices in design representations such as physical modelling, conventional representations, and difficulties in documenting previous thought processes. Also, this study suggested that gaining digital skill needs time and practice. Students experienced difficulties when they started designing as they needed more time to gain confidence and develop the skills required to switch their habitual methods between the two media.

7. Opportunities and Future Directions:

The architectural profession stands at the cusp of a transformational era, poised to be reshaped by the burgeoning influence of emerging technologies. As visionary architects like Frank Gehry, Zaha Hadid, Greg Lynn, Ben van Berkel, and Peter Eisenman articulate the potential for digital design to transcend its current role, a new theory of architecture is starting to take shape. This paradigm shift is not confined to architectural luminaries alone; theorists like Kalay (2004) and Oxman (2006, 2008) have also predicted novel design approaches, methods, and processes that are set to revolutionise the field.

Furthermore, academia's response to this challenge extends beyond curriculum adjustments. Schools of Architecture must become hubs of innovation, driving research that bridges the gap between theoretical insights and practical applications of emerging technologies. Faculty members and researchers play a pivotal role in exploring uncharted territories, uncovering innovative design methodologies, and deciphering the ethical implications entwined with the seamless integration of technology into the built environment.

In conclusion, the architectural profession finds itself on the height of a transformative era, propelled by the advent of emerging technologies and visionary architects. The forthcoming evolution necessitates a reimagining of architectural education, wherein the role of Ai-AAD is deliberated upon with urgency and purpose. Academia's response to this challenge will shape the architects of tomorrow, imparting not just technical prowess but a profound understanding of the symbiotic relationship between human ingenuity and digital innovation.

In summary, while the statement's ambition is captivating, refining it to offer more specifics about the research methodologies, the nature of the new mediums being explored, and the practical outcomes of expanding imaginative skills would strengthen its overall impact and persuasive power.

8. Conclusion:

The study's findings advance the field of architectural concept design by defining the importance and applications of latent diffusion in the field, as well as by demonstrating how final year students and working professionals are utilising the software during the concept stage and working to advance this practise. These results have significant consequences for the long-term structure of architectural design creative practise since they may result in a quick acceleration of the idea design stage and a consequent decrease in burden, allowing them to explore fascinating new paths in greater depth. This depends on pursuing a more exact and rigorous application of latent diffusion models, as well as a more effective and accessible training procedure for them.

Furthermore, this research has shown that young professionals value this technology and that it is already influencing the architectural design process. However, it is obvious that the technology and its creators are impeding human comprehension by concealing the steps used to create and train the models. It is also evident that, although being an intriguing and engaging design tool, it requires expertise to identify the latent data in the outcomes and assign value to it. We are a long way from having a design tool that is 100 percent trustworthy. for Latent Diffusion shows a lot of promise as an Imagination Augmenter if effort is done to educate and harness the method more rigorously inside design. Additionally, integration of the method in a complete workflow currently relies on the human element. There are potential integrations that would make the method extremely more useful, for example by embedding the diffusion generator unto 3D software for the creation of digital assets.

The potential of this study might be further investigated by carrying out much longitudinal research on its use, when contrasted across a complete design and studio pedagogy against a more conventional approach.

The study's findings suggest that image generators are widely used in the field of architectural concept design and that both students and professionals are interested in learning and using these technologies. Additionally, these tools may be used to consistently provide persuasive results. giving significant information for all designers and a fascinating new technique to investigate. This study opens the door to more investigation and advancement in the field of architectural design, encouraging a greater comprehension of the value of AI aided design in concept development.

In conclusion, this paper finds value and benefit in using image generators in architecture by examining their use, confirming their perceived value in the field of concept development, and showing a need for greater training in and the development of an expanded workflow making use of latent diffusion in architecture. This research not only embraces this technology before it is forced upon educators and students but also shows that we require greater transparency and control over its outputs.

In future research, researchers must examine the design and ideation processes holistically to discover where Ai-AAD fits in. Overall, this study stresses the importance of originality in architectural design and how new tools and technologies like AI can help facilitate this creativity.

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COMPUTER VISION AND OBJECT TRACKING FROM VIDEOS

Architecture applications

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Abstract. This paper concisely evaluates video object detection methods in computer vision research, primarily utilizing Python as the programming language. The research contributes to architecture and urban design discussions, employing the Lucas-Kanade optical flow technique to track pedestrians and refine 2D projections. The study aims to enhance the efficacy and understanding of movement behavior patterns in open areas with potential architectural and urban applications. By harnessing object-tracking technology, various benefits arise, including improved client-designer communication, enhanced decision-making, reduced manual workloads, and cost savings by mitigating human errors during field surveys. Case studies, including the Library Plaza at the American University in Cairo (AUC), further illustrate the advantages of implementing these techniques in urban open spaces.

Keywords: *Object detection, computer vision, tracking from videos, movement behavior.*

ملخص. يهدف هذا البحث إلى تقييم طرق كشف كشف وتتبع حركة الناس بشكل آلي عبر الفيديو المستخدمة حاليًا في أبحاث رؤية الحاسوب، باستخدام لغة البرمجة بايثون بشكل رئيسي، بهدف تحسين الكفاءة وفهم أنماط سلوك الحركة. كما يقوم البحث بتسليط الضوء على عمليات هذه التقنيات واستعراض تطبيقاتها الممكنة. بالإضافة إلى ذلك، يُذكر في هذا البحث بعض الفوائد الرئيسية لاستخدام تقنية تتبع الحركة في المساحات الحضرية المفتوحة، مثل تحسين التواصل بين العملاء والمصممين، وتعزيز القدرة على اتخاذ القرار، وتخفيض الأعباء اليدوية، وتحقيق التوفير في التكاليف عن طريق الحد من أو إلغاء التكاليف الزائدة الناجمة عن أخطاء البشر خلال عمليات المسح الميداني. ويختتم البحث بمناقشة دراسات حالة ذات صلة بالموضوع، مع إلقاء الضوء على احدى الساحات الداخلية فى الجامعة الأمريكية بالقاهرة لإبراز هذه المزايا بشكل أكبر.

الكلمات المفتاحية: *كشف الكائنات، رؤية الحاسوب، التتبع من الفيديو، سلوك الحركة.*

1. Introduction

This study examines object detection and tracking in computer vision, focusing on tracking methodologies and theoretical frameworks. It introduces an automated approach to observing human mobility patterns in unobstructed environments, enabling precise tracking of multiple individuals and extracting their movements onto two-dimensional schematics. This methodology offers insights into movement patterns and holds potential for broader analytical applications. Although tracking objects is not new in general, but having a 2D projection of the tracking lines within CAD tools opens new possibilities for using the outcome in various analyses. It could be transferred to the GIS environment in future research.

The discourse encompasses diverse aspects, such as image segmentation approaches, Bayesian filtering models for multi-object tracking, precise trajectory prediction via Kalman filters, and the integration of advanced deep learning techniques like YOLOv3 or SSD. The practical utility of these methods emerges prominently in the context of efficiently monitoring construction sites. These techniques prove valuable for effectively monitoring open spaces using video camera feeds across large areas within tight time constraints.

We implement a straightforward object tracking technique in an open plaza situated within the American University New Campus in New Cairo, Egypt. We focus on tracking objects within video frames while concurrently displaying their positions on the plaza's 2D layout. Although the concept of geo-referencing tracked objects and visually representing them in both 2D and video formats seems uncomplicated, it remains a scarcely explored area in research. It is primarily available in select closed-source commercial software solutions. An alternative approach involves the utilization of GPS trackers for spatial referencing of individuals' movements; however, its application in random and uncontrolled environments or for monitoring a substantial number of users without suitable equipment is challenging (Mohareb and Maassarani, 2019; Mohareb and Omar, 2018).

Defining the terms of object detection and tracking is essential before delving into more details. The process of recognizing a moving or non-stationary item in a video stream is known as object detection. It is the first and most important stage in tracking moving objects. Object identification is the process of detecting occurrences of semantic objects of a specific sort (such as people or cars) in sophisticated images and recordings. It is a computationally challenging technology connected to image processing and computer vision. Object detection is the foundation for many other computer vision tasks, such as instance segmentation, image captioning, and object tracking. On the other hand, object tracking is the act of following a single or numerous objects in a video over time. It entails finding the object in each frame of the video and matching it to the identical thing in the previous frame.

Object tracking is used in surveillance, traffic monitoring, and robotics to monitor the movement of objects in a video (Wahab et al., 2022).

The main benefit of using object detection and tracking for architectural projects is that it enables improved safety measures through increased monitoring capacity with cameras placed at strategic locations throughout a building's surroundings, such as people counting features that count individuals entering/exiting certain rooms.

2. Computer Vision in Architecture and urban planning

The emergence of computer vision (CV) has gained prominence, particularly following advancements in camera hardware and software development. Its integration into mobile phones has facilitated widespread access and utilization. Concurrently, the pervasive adoption of machine learning and artificial intelligence has opened novel avenues for computer vision applications, especially in the domains of architecture and urban design.

In their assessment of CV in urban analytics, Ibrahim et al. (2019) emphasized the advancements in various tasks, including semantic segmentation, object tracking, and scene interpretation. They emphasize the popularity of deep learning due to its ability to handle various complicated data types and the importance of assessment measures like precision, recall, and the F1 score (Ibrahim et al., 2019). Due to CV technology, the evaluation of the urban landscape is changing, including 3D and VR design. Overcoming conventional constraints makes it possible to depict plant landscapes using a variety of expressions, such as drawings and animations. Using CV and multimodal interaction theory is one of the methods used to investigate marine urban botanical landscape design (Yuan et al., 2023).

Computer vision and Google Street View imagery help map user interactions around transit stops. It provides urban designers, planners, and architects with information for user-centered transit stop designs by evaluating elements, including pedestrian flow, safety, and thermal comfort (Wael et al., 2022). As a result, Microscale streetscape feature recognition relating to pedestrian activity is made possible. Deep learning algorithms could replace human-based audits by accurately auditing neighborhoods and identifying relationships between microscale features and macroscale walkability (Adams et al., 2022). Another study introduces an innovative approach that combines Street View Imagery (SVI) and Computer Vision (CV) with traditional geospatial and remote sensing data for comprehensive Public Open Space (POS) assessment. This method automates the evaluation of POS, which is vital in urban areas, eliminating labor-intensive processes. SVI and CV offer detailed insights and a human perspective in urban environment research. The research develops both objective and subjective indicators, utilizing CV algorithms to extract visual features. Through a case study of 800 POS in Hong Kong and Singapore, the study devises a methodology to predict both subjective and objective scores. Ultimately, the research concludes that SVI can revolutionize POS assessment, extending its scope to less-explored off-road areas and contributing to innovative urban planning approaches (Chen and Biljecki, 2023).

Health is another domain where CV can contribute. Convolutional neural networks and Google Street View photos are used by CV to classify constructed areas. It provides insights into studies pertaining to health by identifying associations between neighborhood characteristics and chronic diseases (Yue et al., 2022).

Pedestrian and vehicle movement analysis became an essential topic related to CV. Various robust frameworks utilize CV and deep learning techniques to analyze pedestrian flow statistics from video data. Manual pedestrian behavior analysis through surveys is labor-intensive, making automated video analytics a more effective solution. Existing pedestrian tracking and attribute recognition methods face challenges like occlusion and appearance variations, leading to inaccurate flow data. To address this, a study proposes an improved methodology involving high-level attributes, a multi-cue similarity measure for identity matching, and a probation mechanism. Evaluations demonstrate enhanced tracking robustness, with trajectory and attribute data generating detailed pedestrian flow statistics for different groups. This framework supports informed urban planning, design decisions, and pedestrian movement pattern analysis, while also offering insights for future research in enhancing pedestrian tracking techniques (Wong et al., 2021).

CV could also be used in landscape analysis. A study used a computer vision method and machine learning in response to the trend toward people-oriented urban design to extract street tree crowns from Google Earth satellite data. It discovered four trends linking the spread of trees and the number of pedestrians. The mismatch between evergreen and deciduous trees highlights the necessity of giving evergreen planting more consideration. The study advises arranging street trees with pedestrians in mind (Li and Ma, 2022).

To monitor the evolution of vernacular courtyard buildings with roofed courtyards (CBR), a framework utilizing advanced computer vision (CV) technology, including convolutional neural networks (CNN) and high-resolution remote sensing images (HR-RSIs), is employed. The framework employs an expert module for scene analysis, a CV module for automated detection, an evaluation module with thresholds, and an output module for data analysis. The study examined 24 villages in southern Hebei from 2007 to 2021. This research framework aids in monitoring vernacular building evolution and discerning CBRT adoption patterns, setting the groundwork for understanding the CBR phenomenon and promoting CBRT optimization (Wen et al., 2023).

CV could also work in urban metro transit networks using a deep learning framework to predict passenger loads and train headways in real time. The approach treats the short-term prediction as an image completion task, representing train journeys as images with pixels denoting departure details and load. The methodology accommodates metro line constraints and explores various deep-learning architectures, including novel transformer-based designs. The research extensively analyzes and compares models using a real Paris metro line 9 dataset, collected over three years. The dataset includes diverse scenarios like strikes and lockdowns, facilitating the evaluation of model robustness. The proposed approach encodes train journeys using image representation, employs inpainting for departure prediction, and employs attention mechanisms to highlight significant contributing factors. The research contributes to robust forecasting models and assesses their limits in atypical situations (Bapaume et al., 2023).

Computer vision is also used in the field of heritage archiving through the method of photogrammetry, in a study that documents and compares arched and vaulted entrances of historic buildings in old Tripoli, Lebanon, employing low-cost photogrammetry to contribute to safeguarding endangered monuments. The methodology involves mobile phone camera surveys and photogrammetry software for 3D models. Interviews with historians and custodians supplement the findings. The research underscores the efficacy of affordable photogrammetry that relies on CV, notes its limitations, and asserts its role in identifying monument significance and assisting safeguarding processes (Mohareb et al., 2023).

3. Object tracking versus object detection

Object tracking refers to estimating or predicting a target object's position in each video frame following its initial placement. On the contrary, object detection involves identifying a target object within a video or image frame. The object detection process operates successfully only when the target image is distinguishable within the input. If any interference obscures the target object, it becomes undetectable. Object tracking is designed to trace the object's trajectory even in the presence of occlusions.

TABLE 1. Comparison between object detection and object tracking – Source: various sources, as indicated in the table cells.

Parameter	Object Detection	Object Tracking
Objective	Initial detection of objects of interest.	Maintaining the trajectory of objects over time.
Computational Complexity	Generally higher due to the need for precise localization and feature extraction (Ren et al., 2017).	Comparatively lower as tracking builds upon detected objects (Leal-Taixé et al., 2015).
Real-time Processing	Often slower due to complexity, impacting real-time applications.	Designed for real-time applications, capable of leveraging previous frames.
Robustness to Occlusion	Prone to errors when objects are partially obscured.	Can handle occlusion to some extent by predicting object movement (Bae et al., 2017).
Multiple Object Handling	Detects multiple objects but may struggle with dense scenarios.	Tracks multiple objects efficiently by maintaining their trajectories (Bewley et al., 2016).
Object Tracking Algorithms	Kalman Filter, Particle Filter, Mean-Shift, DeepSORT	Kalman Filter, Particle Filter, Mean-Shift, DeepSORT, BOOSTING, MIL, KCF, CSRT, Medianflow, TLD, MOSSE, GOTURN, Lucas-Kanade optical flow
Python Libraries	OpenCV, YOLO (You Only Look Once), Faster R-CNN, and others	OpenCV, PyTorch, TensorFlow, SORT, DeepSORT, and others
Methods Used	Convolutional Neural Networks (CNNs), Region Proposal Networks (RPNs)	Optical Flow, Feature Matching, and Appearance Model
Use Cases	Applications requiring precise object identification (e.g., image captioning).	Tasks demanding continuous object monitoring (e.g., surveillance).

Object tracking is a pivotal task in computer vision, involving the identification and continuous monitoring of objects within videos or sequences of images. Numerous object-tracking methods and Python libraries are accessible, each carrying distinct advantages and constraints. The chosen tracking method relies on specific application requisites, including object and background intricacy, tracking speed and precision, and available training data. MeanShift and CAMShift represent swift solutions suitable for objects with consistent appearances, whereas Optical Flow tracking excels at handling intricate motion patterns. Deep learning-based tracking methods exhibit heightened accuracy but demand substantial training data and computational resources. Kalman filter tracking is apt for scenarios involving noisy or incomplete measurements but might falter with non-linear motion.

The research uses the Lucas-Kanade optical flow technique for tracking objects in the given Python code. This technique tracks objects' motion from one frame to another in a video sequence. When comparing Lucas-Kanade optical flow with another method, such as Mean-Shift tracking, the choice should depend on the specific characteristics of the object-tracking task. Lucas-Kanade is suitable for tracking specific points and capturing small, linear motions, while Mean-Shift is effective for tracking objects based on color and appearance histograms, adapting to changes in scale, and handling occlusions. When selecting the appropriate tracking technique, it's essential to consider the nature of the objects being tracked, the computational resources available, and the desired accuracy. The Lucas-Kanade Optical Flow technique offers notable advantages. It employs a feature-based approach, making it adept at tracking specific points of interest, which is valuable for distinctive objects or landmarks. Additionally, it provides subpixel accuracy for precise tracking and is efficient for sparse point tracking (Mohiuddin et al., 2019) (Leonida et al., 2022). Beyond object tracking, it finds applications in optical flow estimation, image stabilization, and motion analysis. However, it is constrained by its limitations in tracking individual points, struggling with occlusions and significant appearance changes, and relying heavily on initial point selection. Its assumption of small, linear motion restricts its accuracy in capturing complex object motions.

4. Framework of analysis

The initial objective of the research was to track the movement of various objects within an open plaza (AUC Library Plaza at the American University in Cairo, New Campus), primarily focusing on pedestrian trajectories. This involved extracting the paths of these moving objects and subsequently transferring these paths to CAD software for further analysis and visualization. The process involved the following key steps, see Figure 1.

Video-Based Object Tracking: The research started by choosing video footage of the plaza's activity.

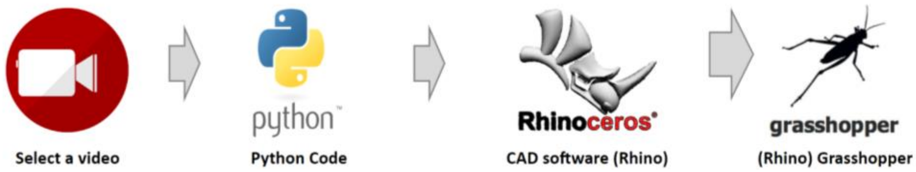

Figure 1. highlights the process of the research framework, starting with capturing the video and ending with Rhino and Grasshopper, which will smooth and project the tracking lines.

A Python code was developed to track the movement of objects within the video, resulting in the generation of distinct tracking paths for each object. Additionally, four reference points were identified to establish the corners of the spatial context. These tracking paths and reference points were saved in a *.DXF file format, see Figure 2.

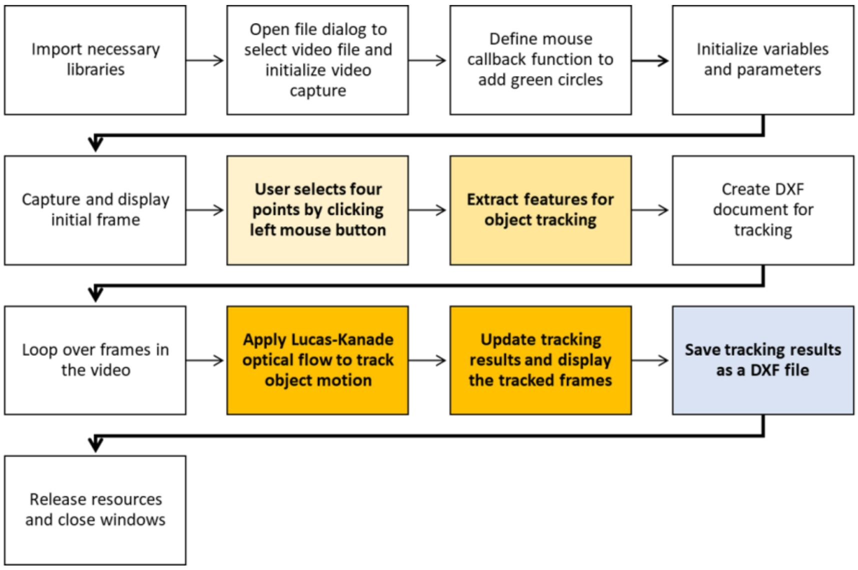

Figure 2. shows the Python code's sequential idea developed by the researcher. The libraries used in this code are: numpy; cv2; ezdxf; tkinter.

Figure 2 shows the key sections of the Python code developed for object tracking using OpenCV and Lucas-Kanade optical flow methods. The initial sections import necessary libraries like NumPy, OpenCV, visualization modules, etc. The next section loads the video file and defines tracking parameters. The core tracking loop applies optical flow to identify object locations between frames and stores the coordinates. Finally, the program outputs the tracking data to a DXF file for the CAD stage.

Utilizing CAD Software (Rhino) for *.DXF File Processing: The *.DXF files generated during the video tracking phase required specific manipulation within the CAD software. This process encompassed cleaning the extracted lines to remove redundant elements and rectifying mirroring issues detected in these lines. To achieve an accurate 2D orthogonal projection of the plaza, we employed Projective2D.rhp Rhino plugin, developed after Sean Tessier, and Vladislav Tutka see Figure 3(A). The objective was to convert perspective-oriented lines from the images into a 2D plan for the same location. This transformation process is referred to as homographic projection, a technique employed in computer vision and presentation systems to rectify distortion and align images. Sukthankar (2001) demonstrated how a camera-projector system can self-calibrate by exploiting the homography between the projected slide and the camera image.

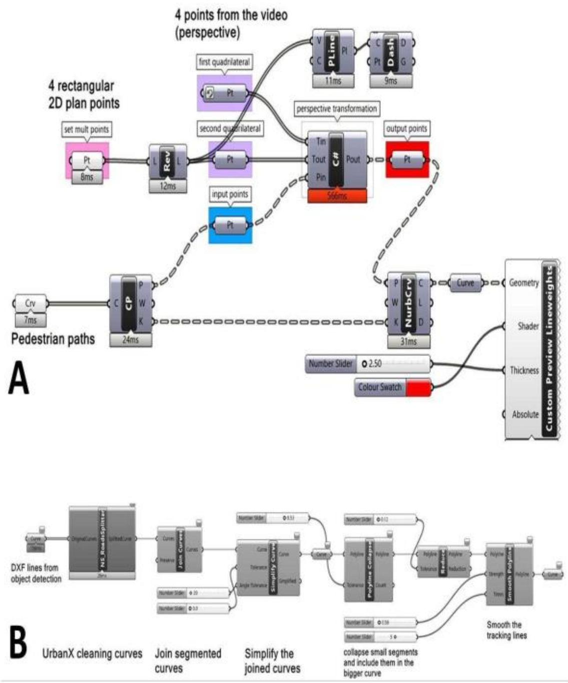

Figure 3. (A) shows the grasshopper workflow developed by Sean Tessier to transfer perspective tracking lines to 2D projection (homography). (B) a grasshopper workflow developed by the researcher to clean the lines extracted from the Python code, simplify, and smooth the tracking lines.

Refinement and Analysis in Grasshopper: After the CAD software stage, further refinement and analysis of the tracked paths were conducted using Grasshopper, a graphical algorithm editor integrated with Rhino. This step involved smoothing and segregating the path tracks extracted from the *.DXF file, ensuring accuracy and clarity in the subsequent analyses, see Figure 3 (B). This step smooths the raw tracking lines extracted from Python using a moving average filter. It removes redundant points to simplify the data. Using a cluster analysis component, the lines are then segmented into separate pedestrian trajectories. The final smoothed, segmented lines provide a clear visualization of movement paths.

5. Library Plaza at AUC New Campus

The AUC Library Plaza, a notable expanse within AUC's new campus in New Cairo, serves an important role as one of the university's largest plazas. It acts as a hub for major entertainment events. The plaza serves as a pedestrian thoroughfare and a social hub for students, faculty, and staff. Electric vehicle transportation is uncommon, usually occurring only when needed.

A carefully chosen vantage point atop the SCE Building—a bridge providing an unimpeded, panoramic view of the plaza—was used to pursue complete observation. It was chosen because it captured a large portion of dynamic movements underneath. The recorded film, which lasts five minutes during peak assembly hour (1:00 p.m. to 2:00 p.m.), corresponds to students, faculty, and staff's collective assembly hour with no teaching activities. As a result, this temporal aperture affords an excellent opportunity to analyze the plaza during its peak population. Monday was chosen because it is known to be the busiest day of the week for students. Notably, avoiding Sundays and Thursdays, which are the beginning and end of the week, on purpose shows that these days have different irregular movement behaviors. Also, Tuesdays are left out because they are set aside for meetings and other academic activities, with fewer classes during these times. This experiment is a pilot study to test the framework and the flow of information from one platform to another.

Following this structured approach, the research successfully achieved its goal of tracking object movement within the open plaza, extracting relevant paths, and transforming them into a comprehensive 2D orthogonal projection for architectural analysis and visualization, see Figure 4 (A&B).

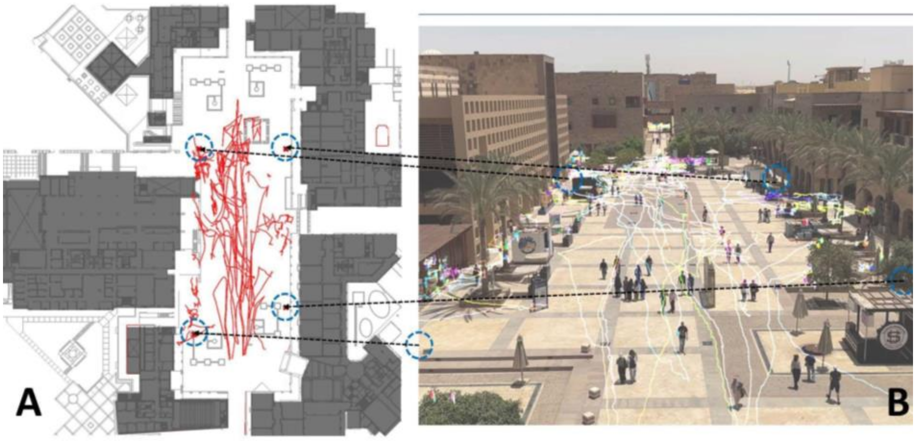

Figure 4. (A) The projected tracing lines on the 2D map of the AUC Library Plaza. (B) shows the last frame of the 5-minute video that captured the pedestrian movement within the Plaza

6. Conclusion and Discussion

Using computer vision techniques in object tracking has become a potential way to increase effectiveness and speed up studies. Even though it is acknowledged that computer vision (CV) cannot reach perfect accuracy, its admirable ability to analyze data at incredible rates is of utmost importance. The speed with which computers can evaluate an hour-long movie demonstrates their ability to reduce the time required for manual evaluation. This temporal effectiveness encourages simplified analysis, allowing researchers to explore more nuanced aspects of the tracked data.

The extraction of tracking lines, which serve as conduits for decoding intricate pedestrian movement patterns and behaviors, exemplifies a pivotal application of computer vision. Derived from video data, these lines function as canvases, tracing pedestrians' trajectories and enabling a profound grasp of their mobility dynamics. On a broader level, extracting quantitative trajectory data enables integration with BIM and GIS platforms for advanced spatial analytics and simulations.

However, a significant drawback lies in the absence of a comprehensive code encompassing all tasks. Although this task is not difficult for a programmer, but it is challenging for architects who are writing codes. Transitioning the outcomes between different programs may result in losing or omitting certain details.

In summary, integrating computer vision techniques into object tracking brings about a significant improvement in efficiency. Swift data processing and trajectory extraction enhance analytical capabilities, saving both time and allowing for a deeper understanding of complex movement behaviors. However, the desire for a comprehensive code highlights the importance of balancing efficiency and coherence to fully leverage the analytical potential of computer vision.

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5.B.

PERFORMATIVE-DRIVEN DESIGN AND DIGITAL GREEN - II

A HYBRID GENERATIVE DESIGN APPROACH FOR OPTIMIZING ENERGY EFFICIENCY IN COMPLEX BUILT ENVIRONMENTS

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Abstract. Architectural design issues in Complex Built Environments have drawn significant attention from contemporary architects. In the conceptual design phase, previous architectural design methods only accentuate the form and function of the design outcome while neglecting whether the result meets the energy efficiency specifications in the current built environment. Therefore, discovering a new method of architectural design by considering the impact of different design elements/modules on the whole life cycle of the building would meet the need for energy efficiency and emission reduction. This paper serves as a demonstration, utilizing the future Faculty of Architecture, Building and Planning (ABP) building at the University of Melbourne's Fishermans Bend innovation campus as a prime example, to evaluate the effectiveness of the SimScale Workbench in creating an energy-efficient parametric building information model and generating Integrated Environmental Solution (IES) simulations to analyze the changes in the energy consumption ratio throughout the whole year. By proposing indoor performance targets based on wind and thermal environment analysis, Architects could use hybrid generative building design methods to formulate design strategies for the complex-built environment from an energy efficiency-driven perspective.

Keywords: *Energy Efficiency, Hybrid Generative Design Method, Complex Built Environment Modeling, Integrated Environmental Solution (IES).*

ملخص. جذبت قضايا التصميم المعماري في البيئات المبنية المعقدة اهتمامًا كبيرًا من المعماريين المعاصرين. في مرحلة التصميم المفاهيمي، تبرز طرق التصميم المعماري السابقة فقط شكل ووظيفة نتيجة التصميم بينما تتجاهل ما إذا كانت النتيجة تلبي مواصفات كفاءة الطاقة في البيئة المبنية الحالية. لذلك، فإن اكتشاف طريقة جديدة للتصميم المعماري من خلال النظر في تأثير عناصر / وحدات التصميم المختلفة على دورة الحياة الكاملة للمبنى سيلبي الحاجة إلى كفاءة الطاقة وتقليل الانبعاثات. هذه الورقة بمثابة عرض توضيحي، باستخدام مبنى كلية الهندسة المعمارية والبناء والتخطيط المستقبلي (ABP) في حرم جامعة ملبورن للابتكار فيشرمانز بيند كمثال رئيسي، لتقييم فعالية مقعد عمل SimScale في خلق الطاقة- نموذج معلومات البناء المعياري الفعال وتوليد محاكاة للحلول البيئية المتكاملة (IES) لتحليل التغيرات في نسبة استهلاك الطاقة على مدار العام بأكمله. من خلال اقتراح أهداف الأداء الداخلي على أساس تحليل الرياح والبيئة الحرارية ، يمكن للمهندسين المعماريين استخدام أساليب تصميم المباني الهجينة لصياغة استراتيجيات التصميم للبيئة المعقدة من منظور يحركه كفاءة الطاقة.

الكلمات المفتاحية: *كفاءة الطاقة ، طريقة التصميم التوليدي الهجين ، نمذجة البيئة المبنية المعقدة ، الحل البيئي المتكامل (IES).*

1. Introduction

As global urbanization continues to accelerate, architectural design issues in complex-built environments have attracted widespread attention from contemporary architects. In the early stages of design, architects tend to deal with the context of the site, the geometrical form, and the function of the building, then evaluate whether these elements satisfy the requirements of the energy efficiency regulations instead of integrating the energy con-sumption of the building into the whole design process, which involves plenty of repetitive and inefficient work. Therefore, exploring a progressive design approach that combines energy-efficient and form-based design is vital. In this paper, an energy efficiency-driven building information model for future new ABP Building is developed on SimScale workbench and simulated through Integrated Environmental Solution (IES) to analyze the changes in energy consumption ratios throughout the year. Specifically, various strategies are optimized by extrapolating the rate of change of total annual energy consumption to obtain an excellent thermally comfortable indoor environment, and reduce building energy consumption, thereby deriving the interaction mechanism of different design strategies (Hamilton & Watkins, 2008). This study explores the hybrid generative design methods for the built environment of complex buildings by coupling the practical mechanisms of different design strategies and proposing appropriate indoor performance goals based on wind and thermal environment analysis.

2. Methodology

Current performance-oriented architectural design predominantly uses a combination of active and passive design strategies to regulate buildings' indoor or outdoor environments. However, multi-objective adaptive design strategies in complex-built environments urgently need discovery (Wang et al., 2022). Architects rely on 3D computer graphics and computer-aided design (CAD) application software to generate and modify the initial ideas during the conceptual design phase. However, the form-finding parameters and the performance objectives are categorized into different phases of the Performative Computational Architecture (PCA) framework in the whole design process (Ekici et al., 2019). Thus, architects have to switch between modeling and simulating settings during the design optimization phase (Shi et al., 2016). Admittedly, when the optimization process comes to the form of the building, architects mainly focus on determining various form-finding parameters, such as the space allocation, aspect ratio of the plan, D/H ratio ('D' means the depth or width of the space, and 'H' means the height of its surroundings), Window-to-Wall ratio, space dimensions, etc. While in actual fabrication, design variables related to the built form are more elaborate. Factors with tremendous repercussions on the final energy demand are building orientation, shape, and the ratio between the external building surface and building volume (Bribián et al., 2011; Lin and Gerber, 2014). Building contractors and construction teams must counterbalance the cost and performance of materials, including U-values/R-values of windows and doors, and holistic cost, which may sometimes conflict with the designer's original vision (Abel, 2007). Meanwhile, the design outcomes' performance objectives, including energy consumption, daylight, solar radiation, thermal comfort, holistic sustainability, energy use cost, and logistics, would be evaluated from a macro perspective, utilizing swarm or evolutionary algorithms, which does not have the same scope as the objectives they were initially focusing on (Shi, 2010). Moreover, the architectural design process is often confronted with multi-objective optimization issues, such as the coupled or mutual mechanism, thus limiting the application of the performance-based technique in actual architectural design practice.

Exploring a new method of architectural design by considering the impact of different design elements/modules on the whole life cycle of the building would meet the need for energy efficiency and emission reduction (Kolarevic, 2003). Performance optimization based on IES simulations and building information models can qualify designers to satisfy the need for environmental interaction mechanisms with various design strategies. Employing intelligent optimization algorithms can furnish resolutions to multi-objective optimization issues and achieve theoretical optimal solutions from the mathematical point of view (Cui et al., 2017). Negendahl and Nielsen (2015) utilized the integrated dynamic model to generate multi-objective genetic algorithms for quickly evaluating building envelope parameters in early architectural design phases. Architects, as the direct beneficiary users of building energy-saving design optimization techniques, are involved with the efficiency of energy-saving strategies or optimization techniques. Hence, how to accurately define the form-finding parameters would be consequential; for instance, investigating how building envelope parameters and geometric configurations affect energy performance (Kheiri, 2018). Originating and utilizing an agent-based model for thermal energy transitions in the built environment will examine which algorithms best claim energy-efficient design optimization issues and conduct rudimentary research on the thermodynamic operation of energy-efficiency-driven strategies (Nava Guerrero et al., 2019). Based on the review of optimization methods in architectural design, the classifications of sub-categories in terms of building performance for swarm optimization and iteration are identified by Ekici et al. (2019) to carry out a typological analysis of the classifications of design elements from an energy efficiency-driven perspective in complex-built environments based on the PCA. The hybrid generative design method also needs to evaluate design strategies combined with energy efficiency-driven year-round energy consumption variability (Pacheco et al., 2012).

The figure below illustrates the workstream of the hybrid generative design method (Fig.1). Designers and stakeholders perform parameter extraction and parametric modeling based on design conditions, objectives, and concepts. Explicitly, constructing a design optimization process based on computer-automated data processing includes performance evaluation and morphological optimization. After completing a certain number of iterations of design optimization, the results are analyzed, and information on the required design elements is extracted.

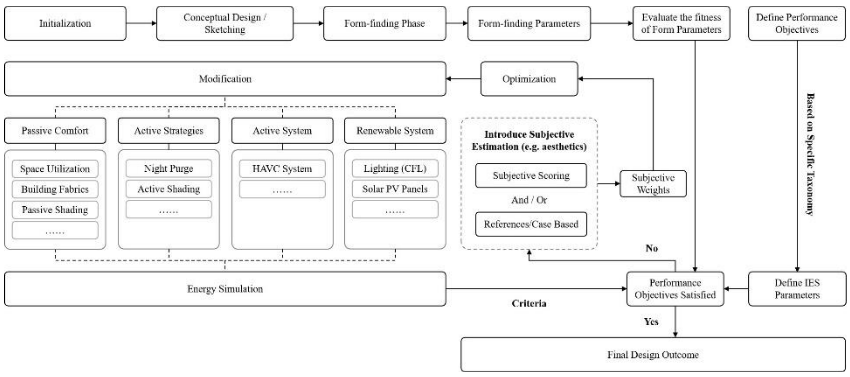

Figure 1. Workstream of the Hybrid Generative Design Method for Modeling.

The research analyzes the reduction in total energy consumption of each specific design strategy through the empirical evidence of a specific case established on the workstream. Subsequently, based on the analysis results, we select suitable indoor performance targets and propose different building design strategies according to the current situation of various wind and thermal environments, derive the coupling relationship of effective mechanisms under the interaction of varying design strategies by projecting the total energy consumption change ratio, optimize different building design strategies to obtain an indoor building environment with good thermal comfort and reduce building energy consumption. This paper utilizes the future Faculty of Architecture, Building and Planning building at University of Melbourne’s Fishermans Bend campus as a prime example, to evaluate the effectiveness of the SimScale Workbench in creating an energy-efficient parametric building information model and generating IES simulations to analyze the changes in the energy consumption ratio throughout the whole year. The dynamic simulation process resulted in the coupled optimization of the construction that would meet Melbourne's indoor thermal comfort design requirement.

3. Baseline Model Analysis

Fisherman's Bend site is located south of Melbourne city, with low building density and vast greenery. The site is bordered by the green public space to the north and the main street to the east; the south and west sides are linked with other adjacent campus buildings. It covers an area of approximately 2500m² (Fig.2). Melbourne is in climate zone 6, which is dry and hot in summer while warm in Australian winter.

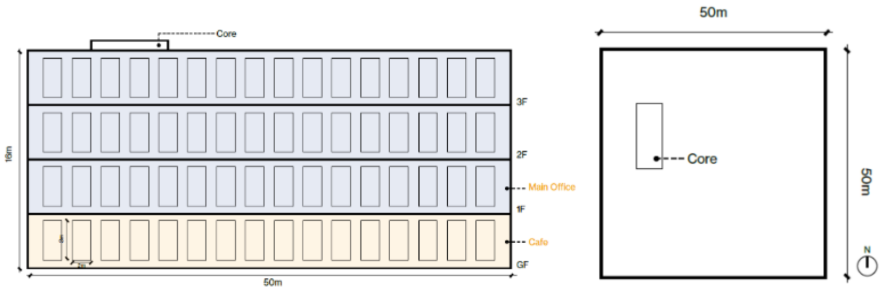

Figure 2. Baseline building Plan and Elevation Diagram.

3.1. SPECIFICATIONS OF THE BASELINE BUILDING

The Baseline building has four levels with a height of 16m, and the total floor area is 10,000m^2 (Table 1). The square plane is 50m x 50m. The core is located in the center of the floor. The large, glazed walls make up 48% of the building's façade, thus requiring a high heating energy load in winter.

TABLE 1. Specifications of the Baseline Building.

Specifications	**Baseline Building**
Location	Melbourne, Victoria, Australia
Type of Building	Commercial Building (Office, Workshop & Studio Classroom)
Number of Floors	4-storey
Floor Height	4m
Height	16m
Window Size	Width 2m * Length 3m
Window to Wall Ratio	48%
Standard Floor Area	2500m^2
Total Floor Area	10000m^2

3.2. BUILDING FABRIC

Around 25% of heat is lost via the roof and wall (Vengala et al., 2021). According to the minimum total R-Value of building envelope elements for commercial buildings in Australia Climate zone 6, the R-Values for the external wall and roof are 1.91 W/m^{2}K and 1.924 W/m^{2}K, which are insufficient for an energy-saving building (Table 2).

TABLE 2. Minimum Total R-Value of Building Envelope Elements for Commercial Buildings in Zone 6, retrieved from *Regulations in the Building Code of Australia, BCA 2015*.

Envelope Element	Australia Climate Zone 6
Roof - Ceilings	
Principal Heat Flow Direction for Roof / Ceilings	
Roof or Ceiling Generally	3.2
Ceilings below Non-conditioned Space	1.6
Walls	
Exterior Wall (all directions)	1.9
Non-exterior Wall	0.95
Floors	
Suspended Floors with Unenclosed Perimeter	1.5

3.3. EXTERNAL WINDOWS

External windows cause a large proportion of additional heat loss (Jack et al., 2016; Albatayneh et al., 2021). The base building is installed with single glazing that has a high U-value: 3.68 W/m^{2}K (Table 3). In summer, the north and west of the building capture a lot of solar gains, while in winter, it requires a high demand for heating energy load due to heat loss indoors. Additionally, the baseline building has no shading system, adversely affecting work efficiency and increasing indoor temperature.

TABLE 3. Baseline Construction Values, source from IES.

Category	R Value	Thickness	SHGC	Transmittance
Internal Floor	0.648 W/m^{2}K	215 mm		
Ground Floor	3.947 W/m^{2}K	5220 mm		
Internal Partition	0.544 W/m^{2}K	110 mm		
Roof	1.924 W/m^{2}K	171 mm		
External Wall	1.917 W/m^{2}K	212 mm		
External Window	0.251 W/m^{2}K	24 mm	0.6577	0.74

3.4. CURRENT BUILDING SYSTEM

The current HAVC system used in the building is the Constant Volume System (Table 4). This system is better suited for single-zone applications where the load experiences minimal change over time (Crawley et al., 2008). The airflow volume of this structure is fixed, and there is no way to reduce it when full airflow is not required. As such, it is energy inefficient and causes uncomfortable temperature variations.

TABLE 4. Current Building System - Constant Volume System, source from IES.

Current Building System Type	**Constant Volume System**
COP (Coefficient of Performance)	0.59kW/kW
SEER (Seasonal Energy Efficiency Ratio)	0.7254kW/kW
Setpoint of Heating System (Café)	18°C
Setpoint of Cooling System (Café)	24°C
Setpoint of Heating System (Main Office)	21°C
Setpoint of Cooling System (Main Office)	24°C

3.5. NATURAL LIGHTING

As shown in the simulation below, the indoor natural light distribution is insufficient (Fig.3, left). Since there is no shading system and large glazed walls, the natural light is too strong near the windows, which may result in an intense glare. Besides, even though the building's outer walls are made of glass, natural light cannot reach around 35% of the space due to the significant depth of field (Fig.3, right).

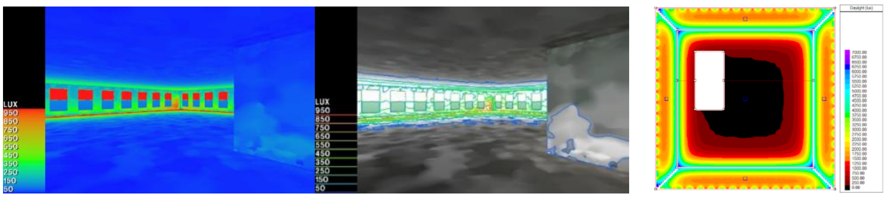

Figure 3. Day lighting analysis, screenshots.

3.6. ARTIFICIAL LIGHTING

The lighting in the baseline building is $12W/m^2$; it uses fluorescent lighting. Florescent light is less efficient than compact fluorescent light, LED light, and other more energy-efficient alternatives (Shahzad et al., 2015; Singh & Katal, 2013). 22.3% of the existing building's total energy consumption is used for lighting. Replacing fluorescent light with a more energy-efficient artificial light system can significantly reduce energy consumption. The figures below indicate that cooling and heating energy consumption is the largest, constituting 45% of the total energy, and the peak occurs during the summer and winter seasons (Fig.4, left). The LES simulation of the baseline model illustrates that the total energy value in one year is 1633 MWh (Fig.4, right). Meanwhile, lighting accounts for 26% of energy consumption, and the monthly consumption remains consistent with no seasonal fluctuations.

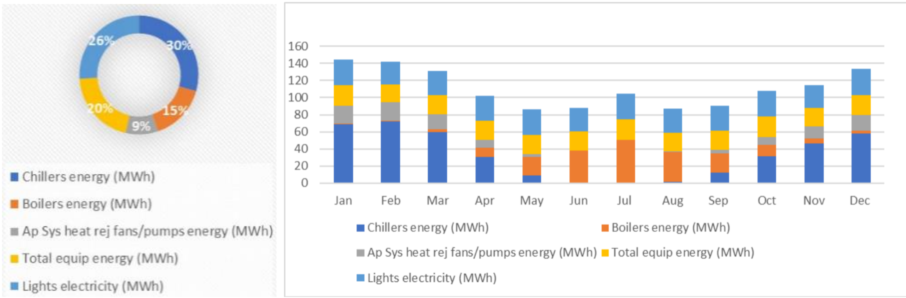

Figure 4. Base model Total Energy Consumption & Breakdown.

4. Design Strategies Analysis

Identifying the specific strategies requires the designers to define and fulfill the multiple design targets and to evaluate and compare the energy simulation results with the initially defined objectives to determine the effectiveness of that design strategy. The estimation in this research is based on the energy consumption for the building's heating, cooling, ventilation, and lighting. To achieve the goal of Net Zero Energy Building, the whole stimulation proposes enhancing four building strategies based on the generic categorization practices of designers aiming to reduce total energy con-sumption, scilicet passive comfort, active strategies, active system, and renewable system.

4.1. PASSIVE COMFORT

The passive comfort design strategy will be investigated in 3 sections: passive space utilization, building fabrics, and passive shading to reduce total energy consumption by implementing the specific design strategies.

4.1.1. Space Utilization: Sky Lighting Core

As mentioned previously, natural light cannot reach around 35% of the space due to the considerable depth of field (Pechacek et al., 2008). A sky-lighting core will replace the original core to solve insufficient natural lighting inside the building. Likewise, installed light-transmitting glass windows on walls and roofs can be opened for natural ventilation in the original closed core by providing a bright and cozy atrium. Hence, incorporating an atrium that allows natural daylight into the center enhances the area with natural light, effectively reducing the energy required for lighting (Fig.5, left). Moreover, the simulation result illustrates that heating and lighting energy consumption decreased slightly, but cooling and total energy also increased minimally due to more solar gain from glazing (Fig.5, right). The increased energy consumption can be compensated for by installing better-performing glass and well-insulated building fabrics.

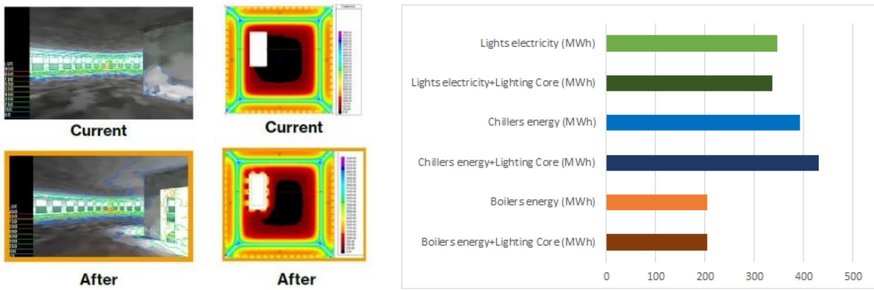

Figure 5. IES Daylighting Analysis (left) & Retrofit Core Energy Simulation (right).

4.1.2. Building Fabrics: Insulation and Energy-saving Glass

Approximately 80% heat loss occurs through the fabric structure in a commercial building (Alam et al., 2011). Adding better insulation can significantly retain and reduce the heat transfer. The addition of better insulation can significantly retain or reduce heat transfer. This section will simulate the changes after retrofitting for each of the three fabrics through increasing R-value.

The roof will be replaced with better thermal insulation materials, preventing heat conduction indoors and outdoors in winter. The layers comprise (from external to internal): stone chippings, bitumen layers, cast concrete expanded polystyrene, cavity, and gypsum plasterboard. The total R-value will be increased from 1.78 to 6. Thus, the simulation result indicates that after replacing the roof fabric with a higher R-value, total cooling & heating energy consumption and total energy have decreased, with a substantial reduction in heating energy (Fig.6, left).

The original 50mm thick glass wool (insulating material) will be replaced with 100mm expanded polystyrene with a lower conductivity value. Two 12mm cavities are added to the wall. Hence, the total R-value is raised from 1.76 to 4.68. And the simulation result demonstrates that the improved external wall with a higher R-value can virtually reduce completed conductive heat loss, reducing annual energy consumption by around 3% (Fig.6, middle).

The base building is installed with single glazing without shading systems, leading to high cooling energy consumption during summer. Replacing the single glazing with the TwinGlaze® - double glazing (Uw-value 1.40, Solar Heat Gain Coefficient 0.53, Visible Light Trans-mission 78%, UV Transmission 0%) implies more improbable heat flow per-formance and better insulating value. The simulation result shows that after replacing the double glazing, both cooling and heating energy consumption decreased (Fig.6, right). Explicitly, the interior safety panel is 6mm toughened safety glass with Low-E nano metallic coating; and the exterior panel is 6mm laminated security glass. This glazing with a high light-to-solar gain (LSG) value reduces solar gain, and there is a lower reduction in visible transmittance VT.

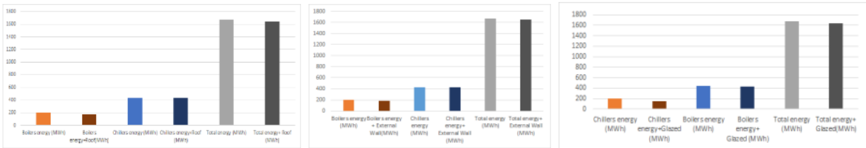

Figure 6. Retrofit Roof (left), External Wall (middle), Glazing (right) Energy Simulation.

4.1.3. Passive shading

Passive shading can effectively control the brightness of sunlight, which can be excluded in summer and admitted in winter via fixed horizontal devices in north windows. The depth of the horizontal overhang should be approximately 45% of the vertical height (Boubekri, 2008). As such, a two-meter-wide horizontal shading is used to shade the glass and reduce glare in the late morning and afternoon. As seen in Fig.7, the fixed horizontal shading effectively reduces excessive solar gain in summer. At the same time, the heating energy increases slightly in winter due to the reduction of sunlight within the building. Overall, annual total energy consumption is reduced after adding the local shading in the north.

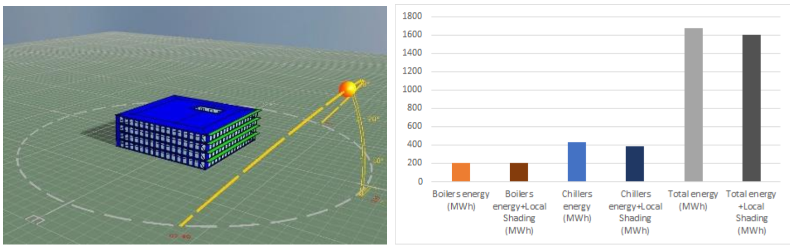

Figure 7. Retrofit local shading strategies energy simulation.

4.2. ACTIVE STRATEGIES

The active design strategy will be analyzed in 2 sections, including night purge and active shading. Unlike the passive comfort strategies, the active strategy intervenes through active deign behavior (Prieto et al., 2018). It selects the outcome that will lead to the most significant reduction in total energy consumption throughout a year.

4.2.1. Macro Flo: Night Purge

The temperature difference between day and night in Melbourne is significant. Night purge is highly effective in pre-cooling the building (hot and stale air is replaced by fresh night-time air). A night purge profile will be set up for window opening. Specifically, when the room air temperature is greater than 22℃, the outside temperature is less than 22℃, and the room carbon dioxide is greater than 600ppm, the window will open from 10 p.m. to 5 a.m. the next day. Besides, the night purge will not run during winter. The result demonstrates that total energy consumption and cooling energy consumption are reduced by 8.2% and 9.1% (Fig.8). Additionally, taking the level 2 west perimeter as an example, the comfort of the environment is enhanced due to the replacement of fresh outdoor air at night.

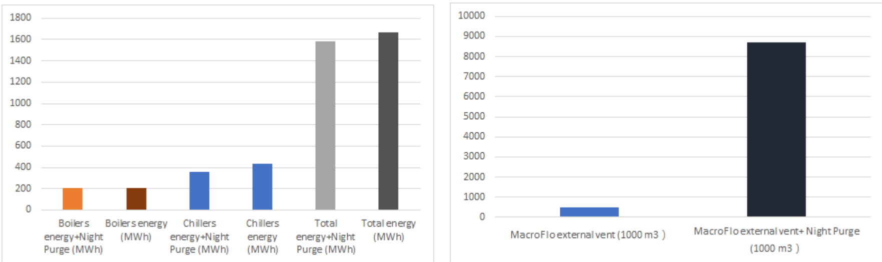

Figure 8. Retrofit night purge simulation, sourced from IES.

4.2.2. Active Shading: Active Shading with Sunlight Senor

The lower sunlight angles in the west and east, coupled with large, glazed walls without a shading system, cause heat to accumulate around the windows, affecting indoor thermal comfort (Islam et al., 2015). Glazing in the west and east will be installed with the external active shading system. The active shading system will rotate by sunlight sensor according to the changing climate conditions, which reduces excessive solar radiation in summer and ensures sufficient indoor natural light. The simulation result demonstrates that though heating energy consumption increases slightly due to solar gain reduction, cooling energy consumption reduces dramatically by 33% (Fig.9, left).

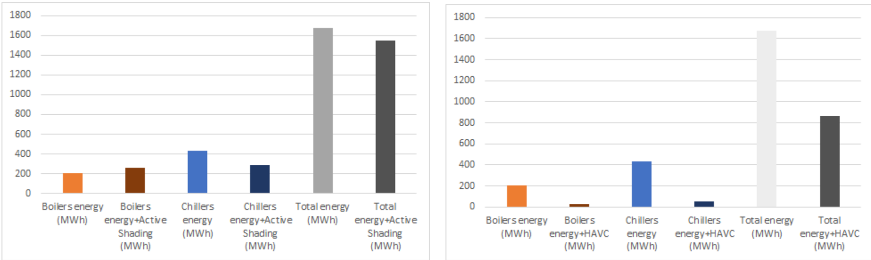

Figure 9. Retrofit active shading simulation (left) & HAVC system simulation (right).

4.3. ACTIVE SYSTEM - HAVC SYSTEM

A more effective Active chilled beams system using natural convective air movement will replace the original HAVC system. Less demand will be placed on chillers, which consume less cooling energy in summer. Active chill beams are better than passive chilled beams as they are more suitable for Melbourne's climate and office typology (Paroutoglou et al., 2019). Ideally, each chiller will have a Coefficient of Performance (COP) and Energy Efficiency Ratio (EER) of 5.09. The simulation shows that the retrofit system performs better, with cooling and heating energy reduced to approximately 88%. Annual total energy consumption decreases from 1671 MWh to 861 MWh (Fig.9 right).

4.4. RENEWABLE SYSTEM: DEVICES (LIGHTING & SOLAR PV PANELS)

Due to the high total energy consumption of lighting (26%), fluorescent light will be replaced by efficient compact fluorescent light (CFL). Indoor sensors will be installed to switch off the light when illuminance is lower than 400 Lux. Moreover, considering the current usage of the roof area, 70% of the roof area (1750 sqm) will be installed with Monocrystalline Silicon Solar PV panels with 19% efficiency. Thus, 425 MWh of electricity can be generated yearly, greater than the building's energy consumption (Fig.10).

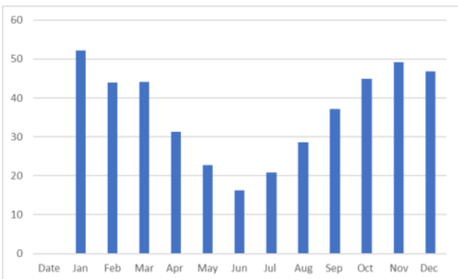

Figure 10. PV Generated electricity breakdown.

4.5. SIMULATION RESULTS SUMMARY

Simulation with the LES reveals how different design strategies reduce total energy consumption (Fig.11). After using the following strategies; total energy consumption dropped from 1633MWh to 644MWh. The decrease in boiler and chiller energy decrease is huge (39.4% reduction).

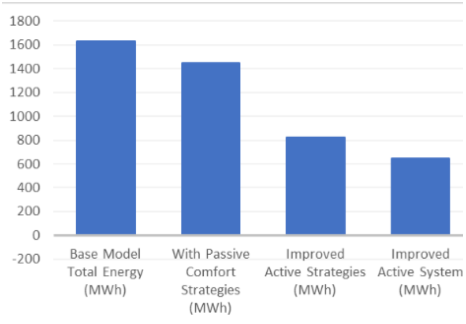

Figure 11. Total energy reduction.

The above strategies lead to the following three equations:

$$\text{Total Energy Use} - \text{Total Equipment Energy} = 387 \text{ MWh} \tag{1}$$

$$\text{Total Generate Energy} = 425 \text{ MWh} \tag{2}$$

$$387 \text{ MWh} < 425 \text{ MWh} \tag{3}$$

To sum up, it meets the demand for *net-zero energy building*.

5. Conclusion and Future Work

Climate change in Melbourne and the building's inherent energy problem are the two main issues driving a net-zero energy building. In this article, the seven selected strategies in project building modeling could be categorized into the four previously mentioned strategies. The final performance of the improved model provides a more comfortable thermal environment, a more attractive space design, and a healthier office environment, achieving a total 51.52% reduction in energy requirements. By proposing indoor performance targets on thermal and light environment analysis, architects could use hybrid generative building design methods to formulate design strategies for the complex-built environment from an energy efficiency-driven perspective. Indeed, the earlier the integrated process of hybrid design intervenes in the building's life cycle, the more effective its building design, construction, energy savings, and overall life cycle will be. Conversely, if building energy efficiency technologies are only used as an afterthought to compensate, the overall design goals are challenging to achieve and very costly to implement energy-saving strategies (Laniak et al., 2013). The definition of spatial comfort will differ when its function and user group change. The current design strategies are based only on the building's function and interior partition. They should be adjusted to the changing demands of new programs or different petitions to achieve sustainable development in the future. In addition, further research may use quantitative indicators to ensure objectivity and strengthen the interactions among design strategies, external or internal performance, and green building policies and regulations.

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ADDITIVE MANUFACTURING OF MYCELIUM COMPOSITES FOR SUSTAINABLE LANDSCAPE ARCHITECTURE

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Abstract. This study explores the potential of mycelium composites as a sustainable and eco-friendly material for landscape architecture in the context of today's global climate and environmental crisis. Mycelium, the vegetative part of fungi, has shown promising properties such as acoustic and thermal insulation, biodegradability, and environmental performance (Vasatko et al., 2022). The central remit of this research is in proposing bespoke computational and robotic fabrication methods and workflows for investigating the performance of mycelial materials and observing their properties and growth response. Taken together, the topic of this paper is to illustrate the application and composition of such fabrication techniques as an integrated multi-material system, capable of combining the complex, organic relationships between clay, lignocellulosic substrate, and fungi with a focus on the potential of such composite materials for implementation within the built environment. Outlined here are the processes and procedures essential to this multi-material fabrication framework, including a detailed account of a series of substrate material mixtures and printed clay scaffold geometries, both of which exhibit properties informed by the material synthesis and fabrication process. We foremost propose the strategic mixing of different substrate types to be 3D printed with clay as a strategy for probing the optimization of mycelial overgrowth and binding to the 3D printed geometries. Subsequently, we proceed in detailing the study's approach and process of 3D printing the mixtures of recycled material, drying the geometry, and sterilizing the final design once inoculated with the mycelium. Ultimately, we motivate this research in pursuit of further understanding of mycelium's material and mycoremediation capacities in service of more environmentally responsive and responsible architectural applications.

Keywords: *Mycelium, 3D Printing, Bio-composite, Biodegradability, Sustainability*

1. Introduction & Background

What is the responsibility of architecture in the 21st century? With this question as a point of departure, our research explores innovative fungal architectural design and fabrication strategies needed for the current age of climate crisis. Through the proposal of a multi-material digital design and robotic fabrication system, the study's experiments focus on the potential of mycelium as a sustainable and transformative building material. Mycelium, the vegetative part of the fungi, has been proposed by several previous studies to demonstrate potential for 3D printing applications. For instance, Jauk et al. (2021) and Mohseni et al. (2023) report the fabrication of a 3D-printed mycelium-based material with tunable mechanical properties. Furthermore, others have reported on the ecological potential and performance of 3D-printed mycelium composites for the built environment (Jauk et al., 2021; Alemu et al., 2022). We extend this line of inquiry by presenting a multi-material design and fabrication platform that integrates a clay-substrate mixture and lignocellulosic mycelium-based composites (MBCs). We implement this digital fabrication workflow using Rhinoceros 7 to design and 3D-print various computed clay geometries and thereafter test the binding and growth of multiple MBC mixtures to the clay scaffolds. Furthermore, we established novel fabrication strategies, integrating the mycelium at different stages of the design manufacture and inoculating after the printing and drying process; the latter of which mitigates against the possible risk of contamination and molding during the drying, which is one of the central challenges with mycelium composites (Dessi-Olive et al., 2022). Additionally, by optimizing the design of computed geometries, we seek to generate the most suitable output for the printing process, load-bearing capacity, and topologies which enlarge the possible printable surface area to support mycelium growth. Through our bespoke digital fabrication platform and design strategies, our experiments culminate in two MBCs structural prototypes. The first is the Mycelial Block, which serves as the foundation upon which we propose the Mycelium Landscape Element. The study positions these alternative organic architectural designs in service of fostering a sustainable interaction between the built environment and the broader ecosystems within which it is embedded. Creating new, natural materials, we are determined to understand how we can design in collaboration with nature and the natural occurrences that happen within these organic processes. By investigating the specific case of fungal architectural design and fabrication strategies, we aim to initiate a broader dialogue among architects, researchers, and policymakers to encourage collaborative efforts to redefine and reimagine the responsibility of architecture in striving toward a more sustainable exchange between humans and nature's own agency.

1.1 THE POTENTIAL OF MYCELIUM AS A 3D PRINTING MATERIAL

Mycelium-based composites are biomaterials that are the result of natural growth. A living fungal mycelium consists of a network of fungal hyphae that can be grown on an organic substrate (Mohseni, A. et al., 2023). The substrate also serves as a nutrient source for the fungi (Elsacker et al. 2020). Mycelium breaks down organic matter into simpler molecules (Walter N. et al., 2022). Fungi are capable of the incorporation of various types of organic waste into composite materials which have potential for future use (Walter N. et al., 2022). When the roots of the mycelium have completely combined the organic substrates, the result is a light and foamy substance known as a mycelium-based composite material (Mycocomposite) (Walter N. et al., 2022). Mycocomposites demonstrate the wide range of benefits that can be achieved by using natural fibre-based materials in place of traditional synthetic composites, such as: low production cost, a competitive potential, reduced energy consumption, potential for CO_2 sequestration when produced on a large scale and, perhaps most significantly, biodegradability (Mohseni, A. et al., 2023).

The low embodied energy manufacturing process used to produce mycocomposites makes them cost competitive with synthetic materials (Jiang, L., et al, 2004). The material is inherently sustainable, as it is derived from completely renewable sources and can be biodegraded under the right conditions, or recycled as a raw material for packaging or as a core material for composites (Jiang, L., et al, 2004). (thus diverting waste from landfills). Mycocomposites are inherently safe–the material is stable when exposed to high temperatures (200–400°C ignition point range) or ultraviolet radiation, and the use of vegetative tissue prevents the formation of spores (a potential allergen and friable particle) if it is made inactive (i.e., killed) before fruiting bodies form. (Jiang, L., et al, 2004).

2. Methods & Testing: From spores to architectural elements

The research methodology was conducted through material experimentation, manufacturing process testing, and a study of design proposals. In order to investigate different material properties depending on the manufacturing process, a set of material mixtures were prepared, which are reviewed in detail in section 2.1. Samples with different geometries were also produced and are discussed in detail in section 2.2. The research was carried out in the following phases: 1. experimentation with materials, 2. testing of different manufacturing processes, 3. development of geometry and design proposal.

The individual designs were derived using different algorithms in Rhinoceros 7 and Grasshopper 3D. In the case of the Mycelial block, the design was created using the differential growth algorithm, which is a simulation and a way of developing shape in biological systems. By developing a distinctive pattern, it is conceivable to challenge the conventional appearance of architectural components and visualize a new aesthetic. The design of the Mycelium Landscape Element was created using Cocoon, a Grasshopper 3D visual scripting interface for Rhinoceros 7. The algorithm produces polygonal meshes from iso-surfaces and enables parameter variation for enhanced sculptural potential.

The primary purpose of this research is to showcase the potential of mycelium-based composites in architecture and carry out artistic experimentation with this material. We believe it is crucial not to undervalue the phase of artistic exploration, as it lays the foundation for further steps towards a deeper understanding and expanded opportunities. The experimental process and observational study have identified properties of mycelium-based composites, including elasticity, compressibility, stiffness, shear strength, tensile strength, and bond strength. Our future investigations will dive deeper into these properties.

The following is a detailed description of the steps involved in the manufacturing process.

Figure 1. Detailed manufacturing process.

2.1. MIXING PROCESS

The substrate is a bulk material that mushroom mycelium can use to grow and obtain nutrition and energy. In our earlier research, we looked at lignocellulose-based substrates and tested various agricultural and industrial wastes for mycelial growth. These included wheat straw, hardwood sawdust, shredded paper, used coffee grounds and corn cob litter. The results of our research indicated that hardwood sawdust is the most suitable material to use in our future studies. Hardwood sawdust was chosen because of its local availability and the ability to control the grain size in an effective manner. The addition of sawdust to the clay mix can create porosity within the structure, which promotes the growth of the mycelium and reduces the overall weight.

To support the growth of the mycelium, wheat bran has been added to the substrate mix. This is a supplement to the nitrogen supply, which increases the speed of cultivation. (Mohseni, A. et al., 2023).

While the combination of substrates improved the mechanical characteristics and affected the integrity and workability of the grown forms, the load-bearing capacity of the tested substrates was not sufficient. As a result, we focused on additive manufacturing and added clay to the mixture. The resulting mixture included 10 kg of red stoneware clay with abrasive W10sf 0-0.2 (25%), 0.8 kg of hardwood sawdust, and 0.5 liters of water. The clay acts as a thickening agent, increasing the viscosity of the 3D printed mixture, preventing ingredient separation, and homogenizing the mixture. It also stabilizes the print to withstand more layers (J. Jauk et al., 2021).

To prepare the mixture for 3D printing, we gradually added the water and sterilized sawdust to the clay. Sawdust had been sifted through a sieve to minimum 2mm size to prevent nozzle clogging. The mixture was then manually kneaded to remove air bubbles, and once it was completely compacted, it was filled into the tank.

2.2. 3D PRINTING PROCESS

2.2.1. Hardware: For additive manufacturing, the Universal Robots UR5, a highly flexible robotic arm was utilized. The UR5 robotic arm has a working radius up to 850 mm. The mixture was extruded using a WASP extruder with 4 mm nozzle to ensure smooth extraction, avoiding occasional blockages but maintaining precision. A pressure of 4 to 6 bar on the material tank was required for printing. Objects produced using 3D printing were considered successful if they met specific criteria, including being stable and not collapsing during or after printing, having adequate size and properties to be sterilized, and having suitable quality for future mycelium cultivation.

Figure 2. 3D printed samples and subsequent filling with substrate mixture.

2.2.2. The Mycelial Block

The geometry developed for the Mycelial Block was generated in Rhinoceros 7 using several Grasshopper 3D plug-ins that perform differential growth simulations. The specific geometry that was created is well designed to serve the purposes of mycelial growth. Benefits of this geometry include the creation of dark shadows, sheltered hiding places, humidity and moisture trapping, and a large surface area for mycelial growth. We are also able to control the load-bearing capacity and infill density by optimizing the design of the calculated geometries and generating the most suitable output for the printing process.

*2.2.3. The Mycelium Landscape Elemen*t

The geometry used for additive manufacturing of the proposed landscape elements was drafted and generated in Rhinoceros 7. Curves were drawn manually in 3D and then wrapped with mesh using the Cocoon plugin. The resulting mesh was then further remodeled using the BoxEdit command, in order to attain a more wave-like and therefore stable geometry for 3d-printing. The result is a porous intertwining structure that would presumably be more difficult to fabricate with any other sort of fabrication technique.

By optimizing the design of the computed geometries, we aim to produce the most suitable output for the printing process, including load-bearing capacity and shapes that increase the printable surface area and support mycelial growth. Robotic technologies for 3D printing offer benefits such as direct fabrication, customized production and convenient transportation. At the same time, high-tech robotics offer economic benefits by saving time, energy and money. Although 3D printing is indeed a high tech process, there are several aspects of the project that can benefit from low tech solutions. Project costs, energy consumption and environmental impact can be reduced by using locally sourced materials such as mycelium, clay and waste substrate.

2.3. STERILIZATION PROCESS

One of the challenges of fabrication with mycelium composites is contamination and molding during the drying process. (Dessi-Olive et al., 2022). Contamination is the presence of unwanted fungus in a mycelium substrate, which can result in long-term problems. To successfully cultivate mycelium, maintaining a sterile environment and working equipment is essential. This includes laboratory conditions, clothing, gloves and alcohol to sanitize hands and surfaces at every step. Our previous research has suggested that pre-inoculation of the substrate with mycelium prior to 3D printing is an unsuccessful method. In order to overcome the issue of contamination, the present study proposes a strategy for the inoculation of the mycelium after the printing and drying process of a mixture of clay and substrate. The printed sample was air-dried for about three days before being filled with a substrate of hardwood sawdust. It was then placed in a special bag and sterilized using an autoclave machine. In the autoclave process, the samples were exposed to saturated steam under pressure at a temperature of 121°C for 15 to 20 minutes.

2.4. INOCULATION PROCESS

2.4.1. Mycelium strain selection

The selection of the mycelium strain is a very important factor in the successful cultivation of mushrooms. Different species of fungi have different mycelial strains with different characteristics (Mohseni, A. et al., 2023). Several factors influence the growth of the mycelium and the material properties of the resulting composites. In addition to the fungal species used for inoculation, these factors include the substrates and additives used, the growing conditions, the cultivation time, and the processing and forming methods. It is possible to improve the mechanical and durability properties of mycelium-based composites by modifying these factors (Mohseni, A. et al., 2023). Two types of mycelial strains, Oyster Mushroom and Reishi Mushroom, were selected because of their specific characteristics. The oyster mushroom (Pleurotus ostreatus) produces fast growing white mycelium and the reishi mushroom (Ganoderma lingzhi) has strong, resistant brown mycelium. The mycelium used in the project was supplied by Držhubu, who are experts in mushroom cultivation. The characteristics of the composite, such as the rate of growth of the mycelium and the color, are influenced by the specific species of mushroom. The requirements for the selection of the mycelium were that the samples should grow as fast as possible and should be strong enough.

2.4.2. Laboratory inoculation

Two types of fungal strains were used, Ganoderma lucidum and Pleurotus ostreatus. Pleurotus ostreatus was used because of its ability to digest a wide range of lignocellulosic substrates (Elsacker et al. 2020). Ganoderma lucidum was used for its strong and resistant mycelial properties. The process of introducing mycelium spores onto a lignocellulosic substrate is carried out in a laminar flow box. Working in a clean laboratory station under safe, dust-free, sterile conditions with a particle-free and germ-free atmosphere plays an important role in the successful cultivation of fungal spores (Mohseni, A. et al., 2023). A laboratory laminar flow box with suction devices and high performance filters provides a cost effective alternative by creating only certain parts of the room and the required clean room conditions exactly where they are needed. One of the experiments that we did not consider successful was the inoculation using liquid culture, due to problems with the survival of the mycelium. We found that the mycelial culture better tolerated a gradual transition: from the Petri dish to the wheat grain and finally to the lignocellulosic substrate. Inoculation with mycelium-inhabited wheat grains proved to be very effective. The use of wheat provides a sugar-rich base for the mycelium to grow on (Jones et al., 2018). The inoculated objects were incubated in a closed plastic container and stored in standard indoor conditions.

2.5. GROWING PROCESS

Initial mycelial growth can be observed on the first day. If there is no visible mold contamination in the following weeks, there is a high probability that the mycelium will survive and fully grow on the substrate. Complete colonization occurs within a period of two weeks to two months, depending on substrate type, fungal species and growing conditions (Attias, N. et al., 2021). Growth characteristics can be altered by changing environmental factors such as temperature, humidity and light. To achieve successful mycelial growth, the ideal conditions involve a damp environment and a darker location away from sunlight, with a room temperature maintained (Appels, F. et al., 2019).

2.6. DRYING PROCESS

2.6.1. Mycelial block

To achieve the desired result, it is necessary to terminate the growth process of the mycelium-based composite. A sufficient heating kills the fungus and stops any further colonization by the mycelium. The fully colonized samples were put into a ceramic kiln and heated by air to 55 degrees Celsius for 24 hours. Nevertheless, drying time may vary depending on the type of clay and the amount of water present. At this stage, the ceramic component of the samples will reach a firing state that is adequate for obtaining the desired tactile properties.

2.6.2. Mycelium Landscape Element

In this concept, the mycelium remains alive. In some cases, the mycelium can be dried at room temperature, which allows the fungus to hibernate. Exposing the material to the desirable humidity conditions again could cause it to resume growth (Mohseni, A. et al., 2023).

3. Findings

3.1 TESTS

The project is currently undergoing testing. In the future, we intend to conduct a more thorough investigation of the mechanical and durability properties of mycelium-based composites.

While the study was focused on determining the design potential of the material, the experimental process led to identifying further observational hypotheses, including: The mycelium acts as an additional binder, leading to a stronger bonding of the 3D printed clay layers than without mycelium; Mycelium increases the tensile strength of the composite material; The rate of growth of the mycelium through the clay is dependent on the thickness of the extruded wall; The mycelium showed accelerated growth rates and greater flexibility after the substrate was finely chopped; Our findings indicate that the mycelial culture adapted more effectively during a gradual transition, resulting in improved growth rates upon transfer to the clay scaffold; The resulting stiffness, tensile strength, and shear strength of the final composite were directly related to the time period of mycelial growth.

3.2 CONTAMINATION AND ITS EFFECTS ON MYCELIAL GROWTH

Based on our research findings, we have developed the following assumptions. Adherence to the sterilization procedure is especially important during the first week, when the risk of mold contamination is at its highest. It is obvious that the mold is inhibiting or even destroying the overall growth of the sample if mold contamination occurs at this stage and affects the mycelium. As the mycelium continues growing and completely colonizing the substrate in later stages, it becomes increasingly resistant to mold. The oyster mushroom has the ability to secrete a liquid in the form of metabolites, which possess mold-killing and digestion properties. These metabolites are part of the mushroom's natural defense system (Park, M.S. et al., 2006). When the mycelium of the mushrooms is robust, it often encircles the mold, confining it to a small area. In some instances, we have observed complete destruction of mold by mycelium in contaminated samples. To ensure a sterile environment for mycelial growth and minimize mold contamination, it is essential to employ appropriate sterilization techniques, maintain cleanliness in the workspace, and adhere to proper hygiene practices throughout all stages of the process.

Figure 3. Occurring molds and healthy mycelium.

4. Prototype proposals

4.1 THE MYCELIAL BLOCK

Through our bespoke digital-fabrication platform and design strategies, our experiments culminate in a series of MBCs structural prototypes. We first and foremost propose the Mycelial Block, a robust structural component that combines the 3D-printed clay-substrate mixture with the sustainable attributes of lignocellulosic by-products, resulting in a durable and environmentally responsible building component. The process involves the controlled integration of the clay-substrate mixture and lignocellulosic by-products, followed by inoculating the materials with selected fungal mycelium strains.

In the process of substrate colonization, fungal growth can be halted through drying or heating the material (Mohseni, A. et al., 2023). Through drying, the fungus is preserved in a dormant state, allowing it to resume growth when moisture conditions become favorable once again. Conversely, heating will effectively eliminate the fungus (Mohseni, A. et al., 2023). The drying or heating of the substrate at any point during colonization will yield composites based on mycelium (Mohseni, A. et al., 2023).

The Mycelial Block is designed with a hollow section that is filled with a substrate. Once the block is inoculated with mycelium, it grows throughout the entire structure. The inner part of the block acts as insulation, while the clay component provides support. Under carefully monitored environmental conditions, the mycelium proliferates and forms a dense network of hyphal threads, reinforcing the material matrix and solidifying the structural integrity of the Mycelial Block. This not only reduces the ecological impact of construction but also fosters a harmonious coexistence with the natural environment.

Figure 4. Mycelial Block.

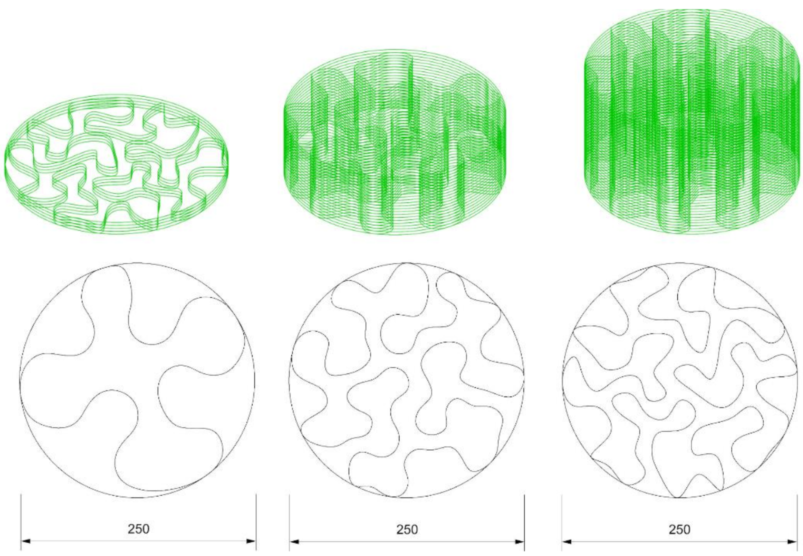

Figure 5. Input geometry of the mycelial block.

4.2 THE MYCELIUM LANDSCAPE ELEMENT

The Mycelial Block forms the basis for our concept of the Mycelium Landscape Element, a prototype for alternative organic architectural design. The main difference is that the mycelial composite remains alive without being subjected to heating, which would kill the mycelium. Our proposal for the future entails continuous innovation and collaboration between architects, scientists, and material experts. Building upon this concept, we introduce the Mycelium Landscape Element, an alternative organic architectural prototype, designed to challenge the traditional role of architecture in addressing ecological and planetary boundaries.

This proposal for mycelium landscape elements explores different ways to benefit the environment. One of the primary motivations for incorporating this particular geometry lies in print paths with high amounts of curvature that can enhance construction stability as well as fostering an improved environment conducive to mycelial growth, enabling it to efficiently navigate and exploit spaces characterized by shadows, cracks, and trails, while simultaneously nurturing a habitat for various plant species to flourish within the construction framework. Promoting prosperity for all levels of nature, considering the well-being and conservation of organisms, populations, communities, ecosystems, biomes, and the overall biosphere. It emphasizes the importance of ecological balance and harmony between human activities and the environment to achieve long-term prosperity and well-being for all forms of life including individual living beings, plants, animals, fungi, and microorganisms.

Figure 6. Implementation of coexistence design in urban areas.

The aim of this Mycelium Landscape Element is to implement this geometry inoculated with mycelium into the urban area, and witness the complete progression of its lifecycle from fungal growth, integration implementation with other forms of plant species culminating to its eventual decomposition in nature.

The organic matter decomposes over time as the plant polymers are replaced with fungal biomass. Fabrication of mycelium-based composites involves the growth of mycelium on organic substrates. The properties and performance of composites are highly variable, depending on fungal species, substrate type, and environmental conditions such as temperature, humidity, and the forming and processing techniques used (Walter, N., et al., 2022).

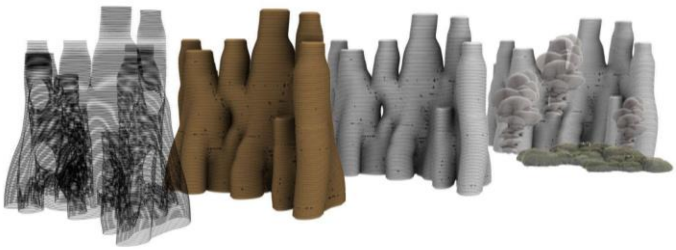

Figure 7. Manufacturing stages of the design proposal.

The study acknowledges the potential in exploring the symbiotic relationships between the mycelium and the plants, witnessing how they coexist and thrive together, contributing to a sustainable and ecologically balanced urban environment creating a living architecture "According to the type of toxins, contaminated soil goes through various chemical and thermal processes to neutralize the contaminants (Stamets, P., 2002)." "Studies have been carried on establishing the feasibility of fungal based remediation; for example, Zitte et al. reports a minimum of 85% reduction in hydrocarbon concentrations, over a four-week monitoring period, by introducing sawdust substrates inoculated with Pleurotus ostreatus (Zitte et al., 2017). Kapoor et al. reports on the effectiveness of different preparations of Aspergillus niger for the removal of various heavy metals from wastewater (Kapoor et al., 1999)"

Mycelium acts as a natural filter, breaking down and absorbing various pollutants and toxins present in the soil, water, or air. These contaminants can include heavy metals, petroleum derivatives, pesticides, and even certain harmful chemicals. "Myco-restoration defines the use of fungal mycelium to initiate the process in which hazardous contaminants are broken down. It favors and supports an ecological reinvigoration of damaged habitats. Mycelium is used to break down and naturally metabolize harmful substances, filtering microbes in terrain and water while contributing to the making of new soil (Stamets, P., 2002)." Myco-remediation is one of four strategies defined within a broader ecological framework of myco-restoration (Stamets, P. 2005; Colmo, C. et al. 2022.)

Figure 8. 3D Printed elements and mycelial growth.

6. Conclusions: Towards Organic Architecture

The ever-growing concerns over environmental degradation and climate change necessitate a paradigm shift in architecture and construction practices. Today's architects and designers are increasingly embracing sustainable, eco-friendly materials and methodologies to minimize the ecological impact of built environments. In this pursuit, mycelium emerges as a promising candidate for revolutionizing the future of architecture, given its unique properties as a bonding agent and biodegradable material.The multi-material design and fabrication framework presented here has been proposed to encourage design and architectural engagement with the temporally behaving properties of biological materials. Through our digital-fabrication framework, we 3D model and robotically print computed clay geometries to serve as design scaffolds for lignocellulosic mycelium based composites (MBCs). In doing so, we put forward the Mycelial block and Mycelium Landscape Element design probes. With these probes we seek to extend the boundaries of architectural representation and to question the role of architecture in addressing ecological and planetary boundaries.

We envision expanding upon our current prototypes through further experiments to characterize the metabolic performance and decomposition of our MBC designs. Additionally, we aim to explore the pallet of diverse mechanical properties mycelium might have under varying growth conditions and to develop optimized means of fabricating structural geometries that best support the MBC lifecycle.

As this research strives to further architectural knowledge and appreciation in the realm of biological building materials, in the future we aim to probe the aesthetic space of practicing architecture with living organisms. We are interested in using our work to question more broadly how biology in an architectural context can challenge traditional notions of symmetry, elegance, and beauty within the field; considering how the active aesthetics of organic processes might shift ways in which we currently conceive of the built environment, its standards of permanence and durability. Ultimately, in our current and future work, we hope to provide an architectural position for engaging with the emerging aesthetics of grown and living materials and their design potential for sustainable fabrication strategies.

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ADAPTING CIRCULAR ECONOMY CONCEPTS INTO ARCHITECTURE DESIGN EDUCATION THROUGH DIGITALIZATION

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Abstract. Circular Economy (CE) is a new production and consumption model aiming to redefine processes sustainably by adopting the "take-make-reuse-recycle" concept in all industries, including the architecture-construction industry. Studies show that we spend more than the current amount of Earth's natural resources and need to reduce global resource production and consumption by a third. This paper investigates the "design by research" method to translate theoretical circular economy concepts into practical village-scale design activities in urban + architecture studio education. The studio aims to develop a design model for circular villages that are affordable, sustainable, and socially connected. Circular villages can collectively positively impact the land and each other. For this study, Sille village in Konya–Turkiye has been analyzed from macro-region scale to micro village scale through the year-long M. Arch graduate urban + architecture design studio. Three main approaches were prominent in developing circular/sustainable planning and design strategies for the village: (1) self-sufficiency in terms of resources, food, energy, and workforce, (2) continuity of natural-cultural values and aspects along with the associative collective memory and contextual relationships and (3) utilizing digital tools in the application of circularity concepts. Exploring the potentials and limits of digital tools to accomplish the circularity principles at urban and architectural design levels brings novel insights to the design notion in architectural education.

Keywords: *circular economy, sustainable urban design, circular village, digitalization, architecture education, design by research.*

ملخص. الاقتصاد الدائري (CE) هو نموذج جديد للإنتاج والاستهلاك يهدف إلى إعادة تعريف العمليات بشكل مستدام من خلال اعتماد مفهوم "الأخذ والتصنيع وإعادة الاستخدام وإعادة التدوير" في جميع الصناعات، بما في ذلك صناعة الهندسة المعمارية والبناء. تشير الدراسات إلى أننا ننفق أكثر من الكمية الحالية من الموارد الطبيعية للأرض ونحتاج إلى تقليل إنتاج واستهلاك الموارد العالمية بمقدار الثلث. تبحث هذه الورقة في طريقة "التصميم عن طريق

البحث" لترجمة مفاهيم الاقتصاد الدائري النظرية إلى أنشطة تصميم عملية على مستوى القرية في التعليم الحضري + استوديو الهندسة المعمارية. يهدف الاستوديو إلى تطوير نموذج تصميم للقرى الدائرية التي تكون ميسورة التكلفة ومستدامة ومتصلة اجتماعيًا. يمكن للقرى الدائرية أن تؤثر بشكل جماعي بشكل إيجابي على الأرض وعلى بعضها البعض. في هذه الدراسة، تم تحليل قرية سيل في قونية-تركيا من نطاق المنطقة الكلية إلى نطاق القرية الصغيرة من خلال استوديو التصميم الحضري + المعماري لخريجي M. Arch لمدة عام. كانت هناك ثلاثة أساليب رئيسية بارزة في تطوير استراتيجيات التخطيط والتصميم الدائرية/المستدامة للقرية: (1) الاكتفاء الذاتي من حيث الموارد والغذاء والطاقة والقوى العاملة، (2) استمرارية القيم والجوانب الطبيعية والثقافية جنبًا إلى جنب مع الذاكرة الجماعية الترابطية والعلاقات السياقية و(3) استخدام الأدوات الرقمية في تطبيق مفاهيم الدائرية. إن استكشاف إمكانات وحدود الأدوات الرقمية لتحقيق مبادئ الدائرية على مستويات التصميم الحضري والمعماري يجلب رؤى جديدة لمفهوم التصميم في التعليم المعماري.

الكلمات المفتاحية: *الاقتصاد الدائرى، التصميم الحضرى المستدام، القرية الدائرية، الرقمنة، التعليم المعمارى، البحث من خلال التصميم.*

1. Introduction

Circular Economy (CE) is a new design-led production and consumption model aiming to redefine processes sustainably. CE aims to regenerate the cycle of nature by reducing material usage and eliminating waste. This concept is related to systems designed focusing on reuse, repurpose, repair, refurbishment, and recycling (EMF, 2013). One of the key aspects of CE is the idea of changing the way of designing and producing products. It takes root from the “cradle to cradle” design philosophy (McDonough, 2002) that aims to make products last longer. CE suggests planning and designing multiple life cycles for one product instead of using materials in a linear, one-time-use process. 10R strategies of CE are defined as Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recovery (Potting et al., 2017).

Circular economy adopts the “take-make-reuse-recycle” concept in all industries. In this regard, the architecture-construction industry must be transformed to adopt circularity concepts. CE foresees transforming architecture professionals to become more responsive to environmental and social realities and a shift towards sustainable and circular design thinking. Circular design thinking and circularity concepts consider systems as integrated, flexible, dynamic, and adaptable to different life scenarios. The principles of CE that focus on optimizing resources, reducing raw materials consumption, and waste management are applicable from urban to material scale. On an urban scale, a circular urban area embeds the principles of a CE across all its functions, establishing a regenerative urban system. These principles enhance environmental quality, economic prosperity, and social equity. Therefore, architecture education should integrate circularity concepts and redesign its curriculum. This paper focuses on integrating CE principles into a village design via design studio practice. The studio aims to develop a design model for circular villages that are affordable, sustainable, and socially connected. Circular villages can collectively positively impact the land and each other. Circular Village aims to keep assets at their highest value at all times, eliminate the concept of waste, and develop local solutions.

2. Methodology and Structure

The presented study explores the implementation of circular economy concepts in the built environment on a village scale in an architectural design studio ("Circular Village: Sille") education setting by adopting the "design by research" method.

Design by research method (Given, 2008) that addresses the specific types of knowledge research can transform theoretical circular economy principles into feasible and practical activities. This design by research method is applied in the studio for deciphering local practices and reviving them by integrating digital technologies into everyday life. The knowledge from conducted research is conceptualized and made operational within urban and architectural design processes.

In the first part of the year-long MArch. graduate urban + architecture design studio. All students first conducted literature research on the concept of circular economy, its relevance to urbanism, architecture, and construction fields, and its impacts on everyday life scenarios. A strong focus is given to self-sufficiency in food production and community involvement, which are the key steps in the transition towards a circular economy on a village scale during literature research. Key strategies and applied cases from around the globe are studied in detail. During the term, various meetings and data exchanges were held with Konya Municipality and Teğet Architectural Office. Then, studio participants were divided into five working groups for the specialized thematic strategies triggering circularity in the village design. First, all groups analyzed Sille village in Konya-Turkiye, from macro-region scale to micro village scale. An excursion to Konya, Sille, and in-situ analyses supports this phase. Participants experienced the existing and surviving culture in Sille and metropolitan Konya independently. Together with personal sketches and small workshop sessions, in-situ seminars, and interviews, they have helped participants to get the essence of the village.

After the excursion, groups started to develop urban and rural circular strategies to transform Sille into a self-sufficient village based on their experience and former literature research on the circular economy concept. Each group focused on a specific theme: agriculture-husbandry, gastro-tourism, culture and tourism, heritage and craft, and digital village. The groups researched how to adapt circular economy principles to a village and how to define new circular strategies within the context. Each group is expected to observe the basic concepts of circular economy in their proposals. These concepts are called the 10Rs of the circular economy: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recovery. Three main approaches were prominent in developing circular/sustainable planning and design strategies for the village: (1) self-sufficiency in terms of resources, food, energy, and workforce, (2) continuity of natural-cultural values and aspects along with the associative collective memory and contextual relationships and (3) utilizing digital tools in the application of circularity concepts.

Utilizing digital tools was important in this overall design process in two ways. Firstly, studio participants actively used digital design tools such as BIM, GIS, 3D point cloud modeling, digital analyzing and diagramming applications, digital drawing and visualization tools, and so on. By using them, participants got the exact information of the area. They worked professionally with real inputs (Figure.1). Secondly, participants proposed the utilization of digital tools and strategies for their village design for a circular vision because digital tools also create a triggering factor in a circular design approach to rethink today's small-scale settlements under globally threatening factors. Digital technologies (DT) make CE strategies possible. Settlements should implement numerous DTs from Industry 4.0, such as big data, artificial intelligence (AI), blockchain, and the Internet of Things (IoT), throughout the entire urban and rural ecosystem to operationalize CE-related strategies. Digital tools can enable and support the implementation of circular economy principles by improving transparency, optimizing resource use, promoting sharing economy models, and facilitating sustainable product design. The combination of circular economy and digitalization can create a more sustainable and efficient economy that benefits both the environment and society.

Figure.1 Random views from point cloud model

Urban/architectural design proposals showed that village-led circular economy principles have promising visions addressing environmental quality, economic prosperity, and social equity. Promoting an interdisciplinary approach regarding the circular economy and internalizing research notions by embedding them into the heart of the design activity is essential in the studio setting. Exploring the potentials and limits of digital tools to accomplish the circularity principles at urban and architectural design levels brings novel insights to the design notion in architectural education.
In this paper, the three group's works are explained by emphasizing their prominent circular village design strategies based on the integration of digital tools due to the limits of the article length. However, all five of them are summarized in tables to visualize the capacity of adopting the circularity principles.

3. Circular Village Design Concepts for Sille

Sille is a well-established, rooted historical settlement that could make good use of its natural resources in the past and become a self-sufficient center that feeds the surrounding small villages. Sille had a circular vision and circular society notion by nature as a village until it lost most of its locals with the population exchange at the beginning of the last century and became the target of tourism-oriented economic development in the last few decades. Referring to the urban-rural memory of the settlement to re-discover local circular social practices that can be applied in current environmental conditions seemed a fundamental strategy for re-thinking Sille in a circular way again.

Agriculture & Husbandry:

Konya is the city with the largest agricultural land in Turkey and is known as "Turkey's granary" with many endemic species, and so is Sille. However, due to the aforementioned population loss, agricultural activities decreased in Sille, and the village became more dependent on the metropolitan city for food supply. Therefore, it was crucial to strengthen Sille's agricultural production potential again and utilize agricultural areas for the local people for a circular future. The main goal of this group was to configure this area using completely local resources of the village for creating a productive society and self-sufficient village by adopting circular approaches with the keywords of zero waste, food safety, and eco-friendly production (Figure.2).

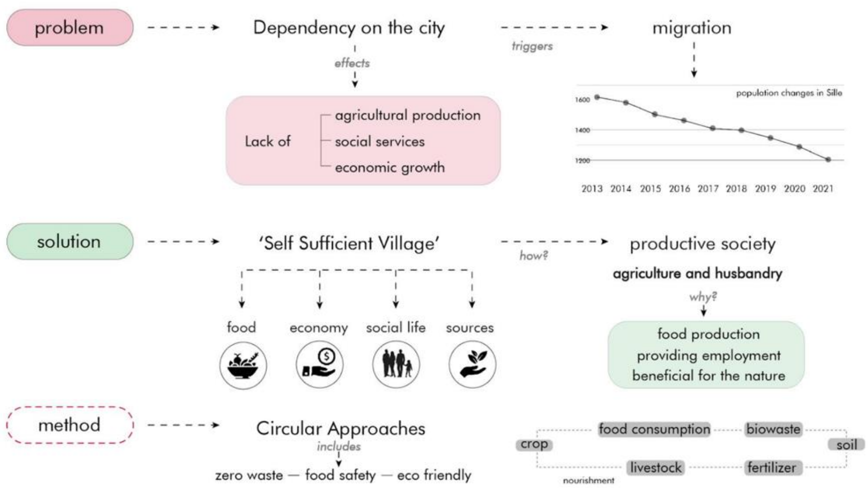

Figure.2 Agriculture-husbandry group mind-map

Integrating society and digital facilities into agricultural production and husbandry was a prominent vision of this design proposal. Therefore, the group proposed alternative production program including community gardens for collaborative working and shared equipment; hobby gardens for individual initiative experiments; healing gardens for endemic species and new employment facilities; agro-tourism activities with educational workshop units and temporary accommodation; organic bazaar for alternative touristic and economic growth; husbandry units for dairy production (Figure.3). Furthermore, smart agriculture facilities are envisioned and promoted in the expected life scenarios. Sensors, remote sensing drone and satellite technologies, artificial intelligence, robot technologies, and image processing technologies can be listed as smart agriculture applications proposed in design for irrigation, spraying, and so on. Besides, measuring the soil temperature and air with digital technologies enables more conscious and deliberate application in agriculture and husbandry production for a circular vision.

Regarding the site plan strategies, the flow directions of rainwater and green area characteristics are analyzed for the newly added buildings. As a result of the analyses, architectural settlement decisions were made in the most optimal way, and natural resources like rainwater or soil were planned to be utilized. Local material resources are proposed to be recycled in construction for a low impact on nature, and existing buildings in the construction areas are proposed to be repaired or reused for compatible facilities. Newly designed buildings are proposed to have modular and transformable characters. In different scales, by adopting the 10Rs of CE. (Figure.4).

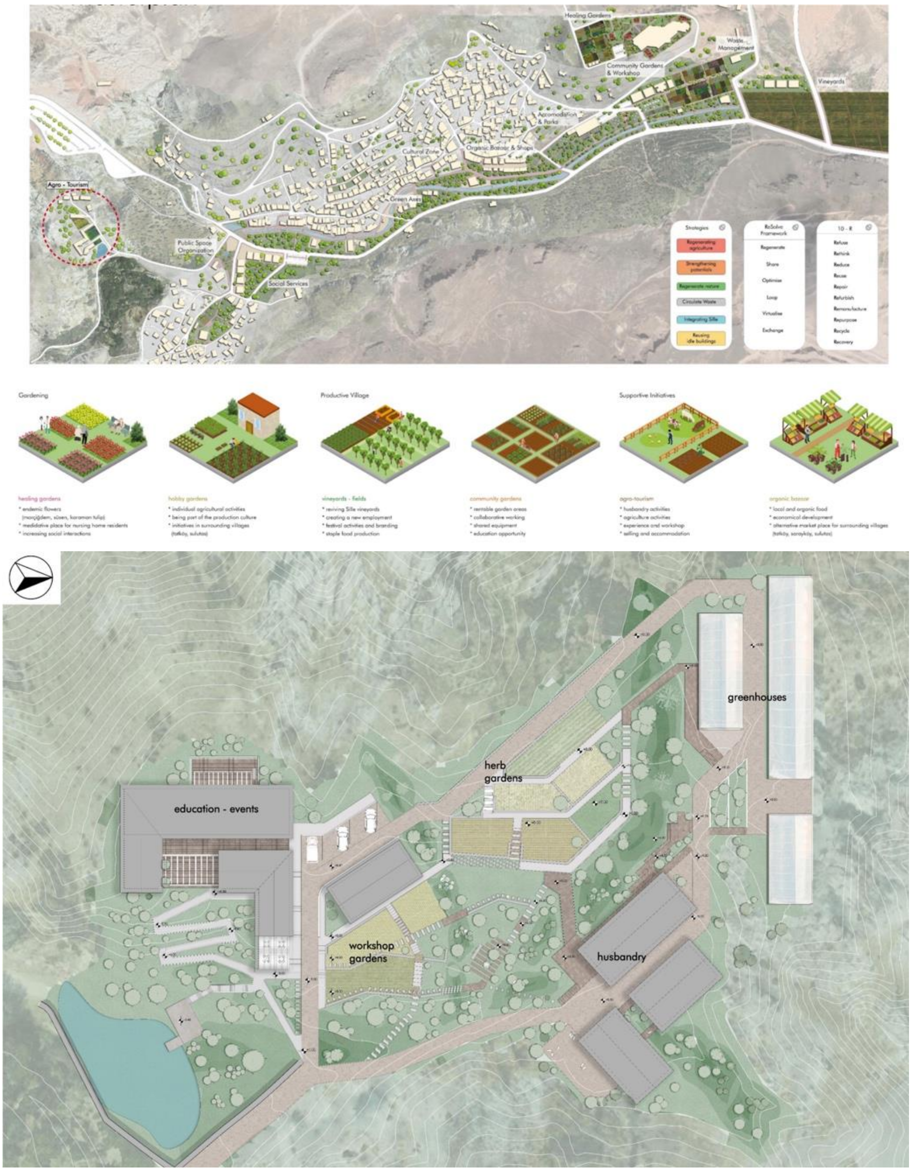

Figure.3 Agriculture-husbandry group design development.

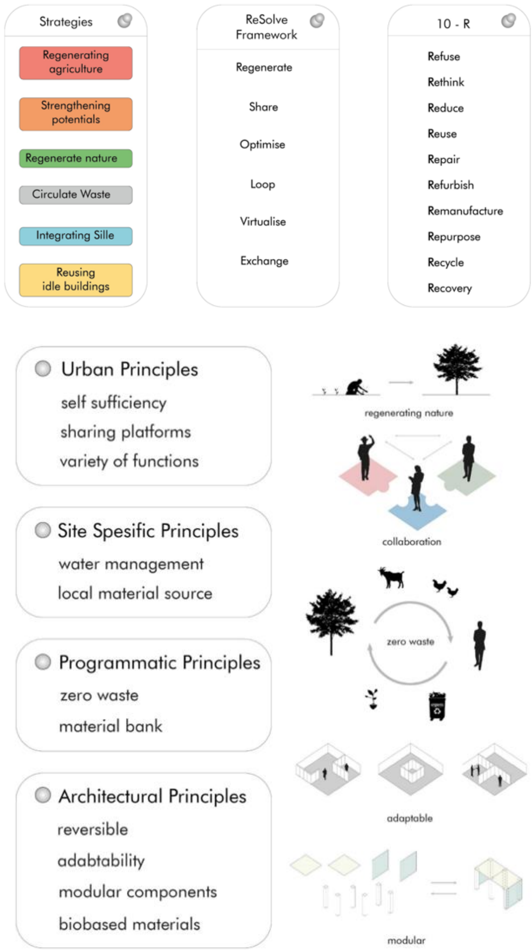

Figure.4 Agriculture-Husbandry group circular design strategies

Culture & Tourism:

Culture and tourism group concentrated on Sille's historical and cultural values and tried to adopt a circular approach for various visions, such as supporting craftsmanship, enhancing architectural quality, revitalizing green space character, and encouraging eco-friendly public transportation. Although Sille is a very important historical center, it has limited weekend daytime activities for local and foreign tourists. Additionally, there is no planned excursion route or defined archaeological areas. This design group offers historical excursion routes from the entrance to the exit of the village to create an experience route and an alternative economic model for food-oriented touristic activities while healing and regenerating the village's public space.

The Culture & Tourism group developed a more detailed proposal for a complex focusing on the entrance to the village, and they created the opportunity to discuss the principles of the circular economy more professionally with this zoom-in approach. (Figure.5) They proposed a light rail system from the city center to the village entrance for individuals and redesigned the existing car park in the area for buses. The complex designed in this area is organized around a modest visitor information center with a VR experience space inside. Visitors can organize their trip here when they arrive at the village, and they can experience past versions of the village from this viewpoint at the terrace through digital tools. (Figure.6) The project also has commercial spaces for local initiatives, workshops for enhancing the interaction between locals and tourists, event space for special public organizations, and open areas for flexible uses such as organic bazaars, fairs, and exhibitions. Water management systems, solar roadways, roof solar panels, integrated natural green spaces, and prefabricated modular structure systems were some of the main circular strategies adopted in this complex. (Figure.7)

Figure.5 Culture-Tourism group design development.

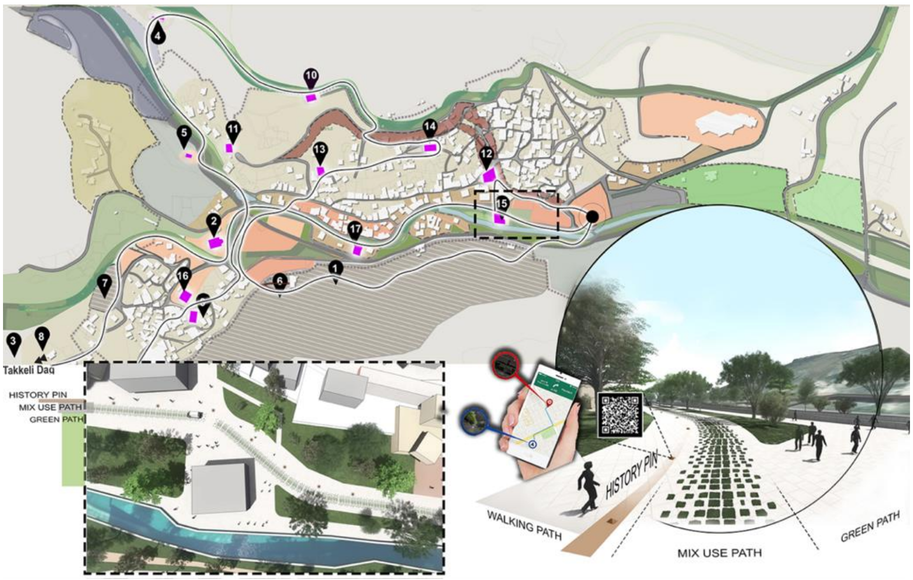

Figure.6 Experience route and digital stops

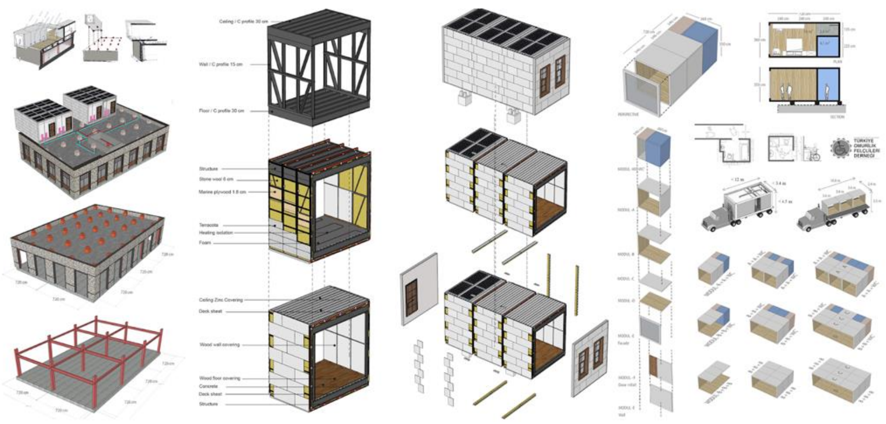

Figure.7 Assembly of modular structure

In different scales, especially in the masterplan scale, adopted urban strategies are evaluated according to the 10R's of the circular economy approach. (Figure.8).

		1/5000 SCALE	1/2000 SCALE	1/200 SCALE
1	RE - FUSE	Creating new alternative ways	X	X
2	RE - THINK	X	Replacing old function with the new	Replacing old site function with the new
3	RE - DUCE	X	Making unused paths usable.	Defining usable land areas
4	RE - USE	X	Defining a camping area on Carpark	Using existing green Using existing natural landfill
5	RE - PAIR	Reviving ancient historical paths	Organizing existing Village roads	Reviving village entrance with new design concept
6	RE - FURBISH	X	Defining an entrance for Village	X
7	RE - MANUFACTURE	X	Using recycled materials for Packacing in commercial areas	To be able to reconfigure the system by enlarging or shrinking the system with the same modules.
8	RE - PURPOUSE	X	New construction proposals with old materials	To be able to produce new functions with a modular system in the future.
9	RE - CYLE	Waste management, plastic and papers Recyling waste materials	Waste management, plastic and papers Recyling waste materials	Gather and transform rainwater.
10	RE - COVER	X	Using existing Konya energy sources for Village	Defining village entrance

Figure.8 Culture and Tourism group circular design strategies

Digital Sille:

Finally, the group aimed to build a digital infrastructure for Sille played an inclusive role, and proposed to design a mobile application (Figure.9) that connects all groups' visions. Unlike all groups, this group offered an e-market where agricultural products grown in the village and second-hand materials are sold, an e-calendar for historical and cultural events, an e-newspaper where various gastronomic or cultural events are published, and shared mobility facilities for eco-friendly transportation. With this application, it is aimed that the tourists coming to Sille can travel more comfortably in the areas recommended by other groups and have the best Sille experience. At the same time, locals can communicate through multiple exchange facilities or share goods and materials to reinforce the community's character. The mobile application integrates AR, NFC, and IoT technologies with the historical village to make Sille more circular. AR is utilized for reviving historical scenery and giving quick information for the past decades of Sille. NFC is used for getting quick information on specific points near landmarks and storing sold materials with a systematic approach. IoT is creating the ability to increase productivity in agriculture, livestock, and energy efficiency in different fields.

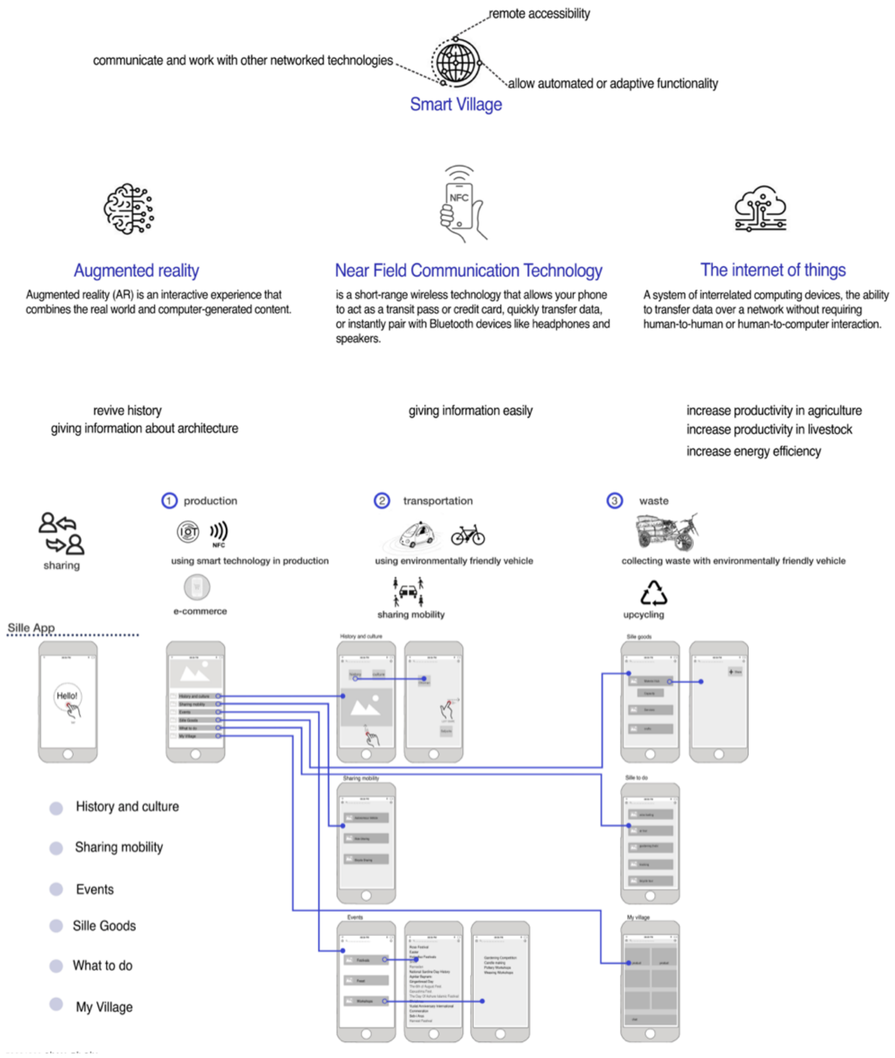

Figure.9 Mobile application interface for Sille

Instead of a fixed architectural space, the Digital Sille group proposed to improve the circularity quality of the open public spaces. (Figure. 10) They redesigned roads to make them compatible with shared mobility, bicycles, autonomous vehicles, and smart lighting. Drone delivery points are also added to the master plan. Different AR points are proposed for some specific places in the village within the mobile application. In this way, it is aimed to make Sille more digital and circular.

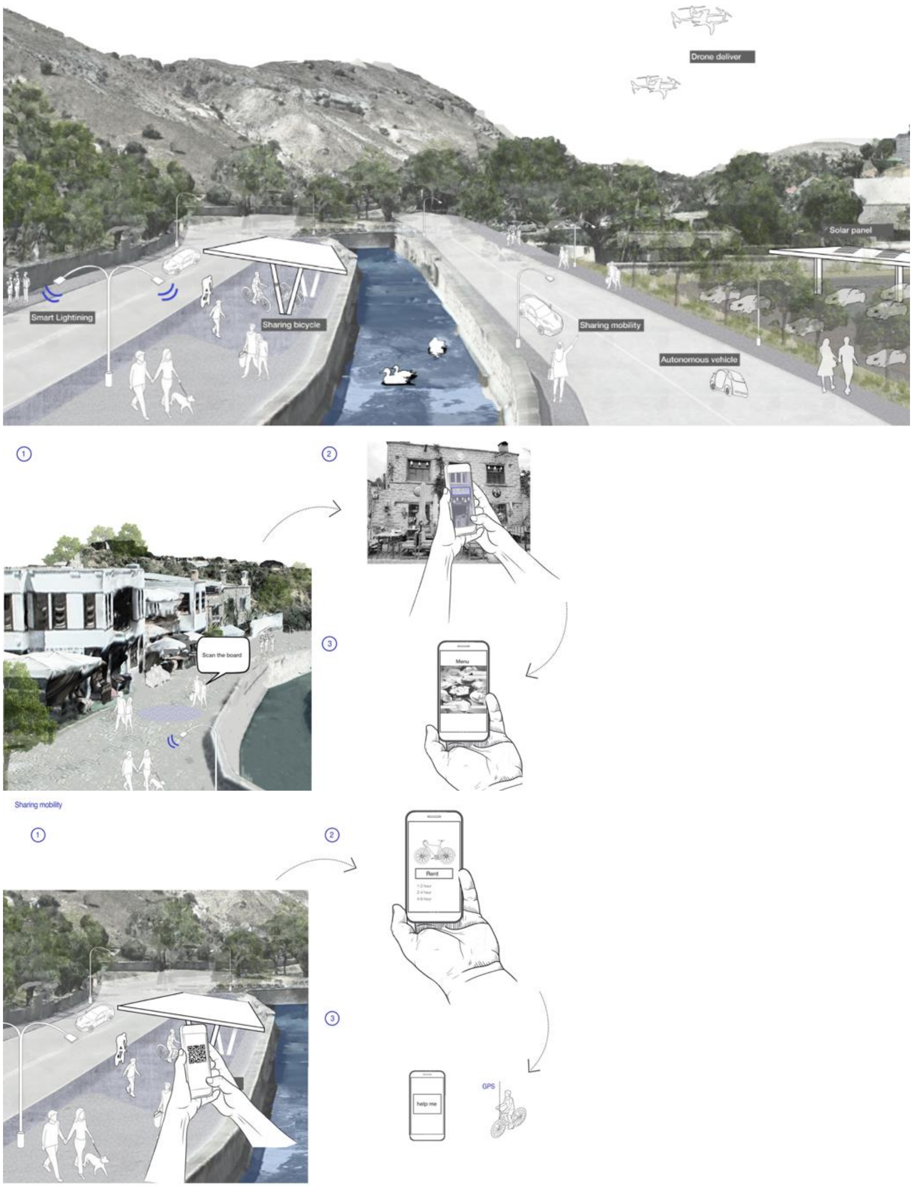

Figure.10 Digital strategies integrated in public spaces

Table 1 summarizes each group's circular design concepts considering the 10Rs of CE strategies. 10R strategies are categorized according to the life cycle process: design, consumption, and return.

TABLE 1. Circular economy (CE) 10R concepts and proposals.

Life Cycle	CE Strategies	Agriculture-Husbandry	Gastro-tourism	Culture-heritage	Digital Village
Design	**Refuse**	Empty fields	Single-use	Globalization	Single-use
	Rethink	Regenerating agriculture	Branding value	Alternative cultural paths	Sharing the space
		Sharing equipment	Distribution methods		Sharing mobility
	Reduce	Waste	Waste	Idle areas & paths	Single-use construction
		Over water consumption	Over consumption	-	Energy consumption
Consumption	**Reuse**	Existing materials	Existing buildings	Existing buildings	Unused materials
			Existing materials	Empty areas	Unused bicycles
	Repair	Existing buildings	Existing pattern	Ancient historical paths	Construction materials
		Existing roads		Existing roads	Furnitures
		Ecosystem			Existing buildings
	Refurbish	-	Demolished areas	-	Historical identity
	Remanufacture	-	Cultural values	Recycled materials	Discarded material
	Repurpose	Idle buildings	Gastro paths	Circular buildings	Material hub
		Cultural path			
		Unused parks			
Return	**Recycle**	Organic waste	Food waste	Waste	Materials
		Water	Water		Waste
	Recovery	Waste	Waste	Waste	Waste

The "Refuse" strategy covers refusing empty fields, single-use, and globalization, aiming to turn Sille into a self-sufficient village by preserving local characteristics and integrating digital technologies. The agriculture-husbandry group suggests "Rethink" regenerating agriculture and sharing equipment through community gardens for locals. The gastro-tourism group rethinks the branding value of Sille's culinary and distribution methods for food, as raw and cooked. The culture-heritage group suggests rethinking the proposal of alternative cultural paths, whereas the digital village "rethink" ownership and suggests sharing the economy by sharing the space and mobility. All groups "reduce" waste, over water, and energy consumption. Also, the culture-heritage group aims to reduce idle areas paths and digital village targets to reduce single-use fixed construction. For the "Reuse" strategy, groups suggest reusing the existing materials and buildings.

Additionally, Digital Village aims to reuse unused bicycles. Agriculture-husbandry group "repair" existing buildings, roads, and village ecosystem. Gastro-tourism group "repair" the existing pattern of the village. The culture-heritage group suggests repairing ancient historical paths and existing roads. Digital Village group targets to repair existing construction materials, furniture, and idle buildings. The gastro-tourism group suggests "refurbish" the demolished and idle areas in Sille and "remanufacture" the nearly-lost cultural values, whereas the digital village group aims to refurbish historical identity and remanufacture the recycled and discarded materials. For the "Repurpose" strategy, agriculture-husbandry repurposes idle buildings, cultural paths, and unused parks; gastro-tourism repurposes gastro-paths; culture-heritage group repurposes circular building involving transformability, flexibility, and low material energy consumption; digital village group repurposes material hub. All groups develop a "Recycle" strategy based on recycling water and waste, both organic and inorganic. In addition, the "Recovery" strategy is based on recovering the waste for all groups.

3. Results: Outcome of Research

Sille is a typical Anatolian village that has multi-cultural layers. Sille was one of the few villages where the Cappadocian Greek language was spoken until 1922. Greeks and Turks inhabited it for over 800 years. In the population exchanges between Greece and Turkey (1923-1924), all Greeks had left the village. The village is currently protected, and renovation efforts were conducted for preservation and touristic purposes. During the design studio, students translated the principles of circular economy, including waste management, sharing society, regenerative design (encourages the development of products and systems that are designed to be reused, repaired, or recycled, reducing the need for new resources and minimizing waste) (Geissdoerfer et al., 2017), and collaborative consumption (encourages the sharing of resources and promotes a shift from a consumption focused culture to a more sustainable and collaborative one) (Bocken, 2014) into urban design principles for the village. These principles are formed to create a circular vision and circular society.

According to 10R strategies of CE (EMF, 2014; Kirchherr et al., 2017; Potting et al., 2017), circular vision and circular society that redefines its connection with historical roots through the principles of utilizing local resources and implementing a circular material flow for sustainability, research, productivity, and cultural preservation, designing products for modularity and transformability, promoting the reuse and refurbishment of materials, and implementing waste collection and processing systems. Three main approaches were prominent in developing circular/sustainable planning and design strategies for the village: (1) self-sufficiency in terms of resources, food, energy, economy, and workforce, (2) continuity of natural-cultural values and aspects along with the associative collective memory and contextual relationships and (3) utilizing digital tools in the application of circularity concepts. Digital Technologies (DT) are enablers of CE strategies. In order to make these strategies, cities should apply various DTs such as big data, artificial intelligence (AI), Internet of Things (IoT), and near-field communication (NFC) technology, which are related to Industry 4.0 to transform the entire village ecosystem to operationalize CE-related strategies.

Table 2 shows the groups' CE actions for urban and building scales regarding self-sufficiency, continuity of natural-cultural values, and utilizing digital tools. Self-sufficiency covers food, energy, water, resources, economy, and space-related topics. Agriculture-husbandry group proposals are based on food production and related socio-economic activities involving community gardens, greenhouses, vineyards, husbandry, and organic bazaars. Also, they have developed a water management system that aims to be a zero-waste ecosystem on an urban scale. For the building scale, they have designed modular transformable buildings and a material bank to be used by the public as a part of the sharing economy. By creating a central platform for collecting, storing, and managing materials, the material bank will allow the efficient use and reuse of resources in the village. Thereby, waste will be reduced, and local production and economic development will be supported. The technical process of recovering materials will involve sorting, cleaning, and repairing them for use in new projects. The recovered materials will then be stored in a material bank, making them available to locals and businesses on the island for their projects. Moreover, the material bank will provide digital access to these materials through a mobile app and website, making it a valuable resource for anyone working on projects on Sille. The gastro-tourism group has also developed a material bank where people can share raw and cooked food and the equipment and modular transformable buildings, which give flexible opportunities for different scenarios in a circular vision. Their urban scale approach is to develop zero-waste restaurants all around Sille.

Table 2. Main CE approaches in urban and building scale.

	Scale	Agriculture-Husbandry	Gastro-tourism	Culture-tourism	Digital Village	Heritage-craft
Self-Sufficiency resource, energy, food, water, space	Urban	Food production	Zero-waste restaurant strategy	Solar energy	Solar energy	Job opportunities based on craftmanship
		Water management		Waste management		
		Zero waste & recycling		Electric vehicle	Recycling	
	Building	Material bank	Material bank	Modular transformable building	Modular transformable building	Modular transformable building
		Modular transformable buildings	Modular transformable buildings	Reusing existing construction materials	Smart lightening	Local material source
				Rainwater harvesting		
Continuity of Natural-Cultural Values	Urban	Regenerating natural ecosystem	Gastro path	New trekking paths	History experience	Preservation of local & traditional craftmanship
			Culinary art	New green path	Natural landscape	
			Festival area proposal	New bicycle path		
	Building	Local material source	Local material source	Restoring historical buildings	Local material source	Heritage Center for local & traditional craftmanship and social interaction
				Design proposal considering vernacular architecture		
Digital Tools	Urban	Sharing platforms	Sharing mobility	Smart transportation	IoT	E-commerce
					NFC technology	
		AR	NFC technology	AR	UI / UX design	
			Mobile app design		UAV – drone delivery	
	Building	-	-	AR	AR	Digital fabrication

The culture-tourism group has suggested using solar energy instead of fuel-based energy by using solar panels in buildings, bus stations, and urban furniture. Waste management is developed as a system for the whole village. Shared electric vehicles (EVs) will be included in the community assets. Also, Sille will offer an EV charging station for public use to facilitate the broader transition to a fully electric transport system. The modular transformable building system with a rainwater harvesting system is designed for the new buildings. Additionally, reusing existing construction materials is another self-sufficiency approach in building scale. Digital Village Group utilizes solar energy and recycling strategy on an urban scale, a modular transformable building system, and smart lighting for the building scale. The heritage-craft group creates job opportunities based on local craftsmanship, including pottery, carpet weaving, and candle making. Creating job opportunities is the key approach to strengthening the circular economy on an urban scale. Modularity, transformability, and local material usage are suggested in building scale.

Continuity of natural and cultural values is crucial to reach a circular economy by closing the loop. Considering socio-cultural contexts, rootedness and authenticity of culture and heritage act as a circular design notion. The agriculture-husbandry group regenerates the natural ecosystem of Sille on an urban scale and uses local materials for the new constructions. The gastro-tourism group designs a gastro path, culinary art workshops, and a festival area. The proposed buildings will be constructed with local materials. Culture-tourism groups have designed the village's new trekking paths, green paths, and bicycle paths. Also, they design new buildings considering the vernacular architecture: materials, ratios, and dimensions. Digital Village Group designs a history experience for the whole village by integrating museums, galleries, boards, points, and maps. Also, they aim to preserve natural landscapes and local building materials. The heritage-craft group aims to preserve local traditional craftsmanship such as candle making, ceramic pottery, textile, and carpet weaving. Additionally, Heritage Center is designed for local traditional craftsmanship and social interaction to create an alternative economic model and foster local employment for a circular future.

Utilizing digital tools is considered as CE enables. Big data, Internet of Things (IoT), Near-field communication (NFC) technology, Augmented reality (AR). The digitalization approaches include user interface / User experience (UI / UX) design, mobile app design, sharing economy, unmanned aerial vehicle (UAV) and drone delivery, smart transportation systems, digital fabrication, and e-commerce. The agriculture-husbandry group proposes sharing platforms for agriculture and dairy production, workshops, and equipment. A sharing economy is a socio-economic system where consumers share in the creation, production, distribution, trade, and consumption of goods and services. This sharing system takes a variety of forms, and usually, information technology, the Internet, and particularly digital platforms facilitate the distribution, sharing, and use of products and services. In this proposal, AR, website, and mobile application serve to spread the sharing platform for agriculture-husbandry. Gastro-tourism has focused on the sharing economy from a sharing mobility perspective and has suggested shared electric vehicles, bicycles, and scooters. Also, the gastro-tourism group has developed a mobile app design to obtain information about culinary, its roots, and restaurant menus.

Additionally, NFC technology is used for ticketing for workshops, asset tracking for the products, payment, and reservation identification. The culture-tourism group proposes a smart transportation system including electric vehicles, sharing the vehicle, vehicle tracking through IoT and NFC, route control, and damage detection. On the other, to inform local people, particularly tourists, about the history and culture of Sille, AR technology is integrated into boards, maps, and walls through QR codes and images. AR is advantageous due to the friendly usage of mobile phones. Digital Village group aims to develop a virtual Sille village to inform, design, and organize through digital technologies. In this regard, the group has developed UI / UX design through a mobile app and a website devoted to Sille. IoT, big data, and NFC are developing "digital" Sille precisely with real-time information to categorize and extract the Sille data. In addition, drone delivery, an example of an unmanned aerial vehicle (UAV), is used for smart delivery systems within the town.

On the other hand, historical buildings and tourist attraction points are introduced via QR codes to the tourists. The heritage-craft group aims to preserve local craftsmanship, including pottery, textile and carpet weaving, and candle making. This objective also includes expanding the local craft techniques and integrating exploratory digital fabrication (DF). Integrating DF creates a new job and research opportunity for the public. Also, thanks to DF, new materials can be used to expand the existing products. In addition, e-commerce will be integrated to increase the impact of Sille's heritage and craftsmanship. E-commerce will include purchasing products (such as pottery, candles, and carpets) and services (such as online workshops for do-it-yourself candle making).

4. Conclusion

This study investigates implementing circular economy principles on a village scale through the circular village concept on Sille. The conceptual circular strategies, on various scales, are developed for Sille. In order to implement these circular strategies, digital technologies must be integrated into this process, as they are crucial in making the circularity concept operational to transform theoretical circular economy principles into feasible and practical activities.

In this regard, circular economy literature is first studied and examined from urban to building scales. Then, five working groups are formed according to the characteristics and needs of Sille with a circular vision. Each group has designed proposals for urban and building scales. The main three approaches are self-sufficiency, continuity of cultural-natural values, and utilizing digital tools. According to the CE concepts and designs, “sharing economy & society,” “material bank,” and “local sources” are the main components to reach circular Sille village.

The sharing economy and society strategy focuses on creating digital and physical platforms that can efficiently share resources on Sille. These platforms include online websites and mobile apps that allow people to easily access and share resources, such as tools, foods, equipment, or knowledge. The overall aim of this strategy is to encourage sustainable consumption and production in the village by increasing the value of products and reducing waste. This approach also emphasizes the importance of collaborative production and being a community, one of the main pillars of the circular economy. The material bank acts as a central platform for collecting, storing, and managing the sources, allowing the efficient use and reuse of resources in the village. Thereby, waste will be reduced, and local production and economic development will be supported. Local sources include local food production, husbandry, heritage, craftsmanship, and natural ecosystems. Preserving and evolving the “local” is also an economic approach in circular strategy. CE highlights the need to develop the local and traditional focus on economic growth to become a more sustainable and transformative economy. Low-threshold projects that prioritize reusing, repairing, and converting existing products-materials-buildings over consuming new ones should be prioritized to achieve this. Furthermore, creating knowledge and awareness about the benefits of a circular economy is crucial to transforming society into a circular community. The strategy suggests using digital technologies such as AR, mobile apps, websites, and QR codes on Sille for this approach. By implementing these approaches, the goal is to create a circular Sille to have a more sustainable built environment that supports the long-term development of Sille. Involving digital technologies such as IoT big data, NFC enables real-time data flow to provide the village with smart transportation, smart lighting, and sharing platforms.

Urban/architectural design proposals in the studio scale showed that village-led circular economy principles have promising visions addressing environmental quality, economic prosperity, and social equity. Promoting an interdisciplinary approach regarding the circular economy and internalizing research notions by embedding them into the heart of the design activity is essential in the studio setting. Exploring the potentials and limits of digital tools to accomplish the circularity principles at urban and architectural design levels brings novel insights to the design notion in architectural education.

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A CRITICAL REVIEW ON RESEARCH THEMES AND TRENDS IN GREEN BIM FOR AEC SECTOR

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Abstract. Green BIM is an emerging concept in the architecture, engineering, and construction industry that combines Building Information Modeling (BIM) technology with sustainable design principles. This approach emphasizes the importance of integrating green strategies into the design and construction process to improve the environmental performance of buildings. It enables designers, architects, engineers, and contractors to analyze the environmental impact of building materials and systems, simulate energy performance, and optimize the use of resources. The aim of the study is to conduct a bibliometric research and systematic analysis on the concept of 'green BIM'. Web of Science database was used to search for publications containing the term 'green BIM'. 252 relevant publications from the fields of construction building technology, architecture, and urban studies were analyzed. It evaluates research themes and trends in Green BIM in terms of publication and citation numbers, research areas, document types, journals, conferences, and books where publications were published, numbers of publications by country, author and co-authorship analysis, and keyword analysis. The keywords were divided into 9 clusters in the VOSviewer and each cluster was examined under a separate title. These titles are urban design, visual programming, design & construction, sustainability, energy efficiency, life cycle assessment, green BIM, project management and green building assessment. The results show that the most current keywords are being evaluated under the heading of urban studies. This situation highlights that, unlike other academic studies, priority is given to urban-scale applications of green BIM Moreover, apart from urban-scale studies, possible topics for academic research involve Life Cycle Assessment (LCA) and the integration of BIM in the LEED certification process. Currently, the industry and prominent publications prefer technical studies due to the extensive coverage of general inquiries.

Keywords: *Green BIM, sustainable design, AEC, environmental performance, bibliometric analysis.*

ملخص. تعتبر نمذجة معلومات البناء الخضراء مفهوما ناشئا في مجال العمارة والهندسة والبناء تجمع بين تقنية نمذجة معلومات البناء (BIM) ومبادئ التصميم المستدام. ويؤكد هذا النهج على أهمية دمج الاستراتيجيات الخضراء في عملية التصميم والبناء لتحسين الأداء البيئي للمباني. فهو يمكّن المصممين والمعماريين والمهندسين والمقاولين من تحليل التأثير البيئي لمواد وأنظمة البناء، ومحاكاة أداء الطاقة، وتحسين استخدام الموارد. ويكمن الهدف من هذه الدراسة فى إجراء بحث ببليومتري وتحليل منهجي حول مفهوم "نمذجة معلومات البناء الخضراء". تم استخدام قاعدة بيانات Web of Science للبحث عن الأوراق البحثية التي تحتوي على مصطلح "نمذجة معلومات البناء الخضراء". تم تحليل ٢٥٢ ورقة بحثية ذات صلة بمجالات تكنولوجيا البناء والعمارة والدراسات الحضرية. وتقوم بتقييم موضوعات واتجاهات البحث في مجال نمذجة معلومات البناء الخضراء من حيث عدد الأوراق البحثية والاستشهادات، ومجالات البحث، وأنواع المستندات، والمجلات، والمؤتمرات، والكتب التي تم نشر الأوراق البحثية فيها، وعدد الأوراق البحثية حسب البلد، وتحليل المؤلف والتأليف المشترك، وتحليل الكلمات الرئيسية. تم تقسيم الكلمات الرئيسية إلى ٩ مجموعات في VOSviewer وتم فحص كل مجموعة تحت عنوان منفصل. هذه العناوين هي التصميم الحضري، البرمجة المرئية، التصميم والبناء، الاستدامة، كفاءة الطاقة، تقييم دورة الحياة، نمذجة معلومات البناء الخضراء، وإدارة المشاريع وتقييم المباني الخضراء. أظهرت النتائج أن أحدث الكلمات الرئيسية يتم تقييمها تحت عنوان الدراسات الحضرية. يسلط هذا الوضع الضوء على أنه، على عكس الدراسات الأكاديمية الأخرى، يتم إعطاء الأولوية للتطبيقات على المستوى الحضري لنمذجة معلومات البناء الخضراء علاوة على ذلك، وبصرف النظر عن الدراسات على النطاق الحضري، فإن الموضوعات المحتملة للبحث الأكاديمي تشمل تقييم دورة الحياة (LCA) ودمج BIM في LEED عملية إصدار الشهادات. حاليًا، تفضل الصناعة والأوراق البحثية البارزة الدراسات الفنية بسبب التغطية الواسعة للاستفسارات العامة.

الكلمات المفتاحية: *نمذجة معلومات البناء الخضراء، التصميم المستدام، العمارة والهندسة والبناء، الأداء البيئـى، التحليل الببليومترى.*

1. Introduction

Throughout the design and construction process, especially in large-scale projects, various stakeholders from different professional backgrounds collaborate to exchange data and ensure successful project implementation. However, the data transfer process can sometimes lead to unnoticed issues during the design phase and result in construction errors. Moreover, decisions made during the design phase can significantly impact the long-term sustainability of the facility after completion (Leite, 2020; Sacks et al., 2018; Garber, 2014). To ensure the correctness of such decisions during the design phase, it is essential to conduct simulations, data analyses, and environmental impact assessments before entering the construction phase (Krygiel and Nies, 2008). The dynamic requirements of projects have caused a shift in traditional construction management and project delivery approaches, with the integration of information technology applications throughout the project's life cycle (Gerrish, Cook, Ruikar, 2016). BIM refers to a comprehensive process that encompasses design, construction, and facility management, while also serving as a technology that enhances communication among architecture, engineering, and construction sectors (Leite, 2020; Deutsch, 2011; Lévy, 2019; Sacks et al., 2018). Its application across all stages of a project's life cycle yields advantages for pre-construction planning, design, construction/manufacturing, and post-construction phases (Eastman et al., 2011).

'Green BIM' has emerged as a prominent term in contemporary discourse, signifying the integration of Building Information Modeling (BIM) with green building practices to attain sustainability objectives (Wong and Zhou, 2015). Despite its prevalence, there remains a lack of academic literature that precisely defines the concept of 'green BIM.' (Darko et. al., 2019). Nonetheless, recent advances in BIM have opened up possibilities for supporting green building applications, leading to the coining of the term 'Green BIM.' Wong and Zhou (2015) characterize Green BIM as a model-based process aimed at generating and managing consistent building data to achieve sustainability goals. The McGraw-Hill Construction Smart Market report further elucidates Green BIM as the use of BIM tools to pursue building sustainability objectives. Wu and Issa (2015) emphasize the combination of BIM with green building principles to foster sustainable outcomes in building development and promote environmental aims. Thus, Green BIM serves as a precious tool in the building design industry, facilitating the seamless integration of sustainable elements into the project lifecycle, with a particular focus on energy efficiency (Alawini et al., 2013). Green BIM facilitates various performance analyses and assessments such as acoustic analysis, carbon emissions, construction and demolition waste management, operational energy, and water usage (Ansah et. al., 2019).

Due to the existing gaps between industrial needs and current academic research, as well as the deficiencies in current conceptual understanding, a comprehensive review of the current development of Green BIM is warranted. An inclusive examination of the existing literature can help establish disciplinary connections in light of the ongoing advancements in Green BIM within the industry, thereby reevaluating academic or scholarly challenges. This process provides significant benefits in identifying areas that require further efforts and, consequently, categorizing the future research directions of Green BIM. A comprehensive review of previous research can be highly beneficial in identifying areas where additional efforts are most needed and understanding which directions would be most productive for future Green BIM research (Wong and Zhou, 2015). The importance and purpose of this study are also to be a small part of contributing to this endeavor. This study aims to conduct a bibliometric analysis to systematically examine the concept of 'green BIM' in the literature. While some existing bibliometric reviews have explored green BIM from a general perspective or within the engineering-construction sectors (Lu et.al., 2017; Darko et. al., 2019) or design-construction phases (Wong and Zhou, 2015). While conducting a bibliometric analysis on Green BIM, it is believed to be important to plan the study in a way that includes urban studies, thus encompassing the upper scale, to provide a comprehensive and holistic understanding. No analysis has focused on the areas related to urban design, architecture, and construction design technology. Examining articles in these domains is essential to discuss sustainability and green design principles in the context of green BIM. Urban design and green BIM have been identified as highly relevant subject areas, particularly concerning decisions at the highest scale. By conducting a bibliometric analysis, this research intends to guide authors towards potential studies and offer general insights into the field. Thus, this study involves a comprehensive evaluation of published research, aiming to ascertain how researchers at the intersection of BIM and architecture collaborate and identify existing gaps and potential in the field.

2. Methodology

This study employed bibliometric analysis to uncover the prevailing trends and advancements in ‘Green BIM’ topic. The flowchart illustrating the steps of the bibliometric analysis is as follows:

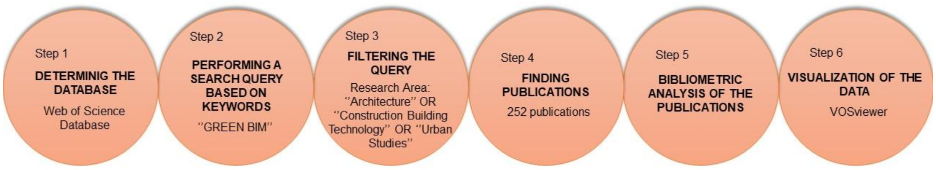

Figure 1: Method of the study

The study focused on publications with the term "Green BIM" within the subject areas of construction building technology, architecture, and urban studies. These selected publications were analysed based on several criteria, including publication and citation years, research areas, document types, publication titles, publication numbers by countries, authorship and co-authorship patterns, publication numbers, and citation analyses by universities and keyword analyses.

By utilizing Web of Science a total of 252 publications, which focused on the topic of "Green BIM," were filtered from the Web of Science database. These filtered publications fell under the subject areas of "Construction Building Technology," "Architecture," or "Urban Studies." Using the VOSviewer, this study generated bibliometric charts, maps, and clusters, employing network links and clear visual graphics such as circles and labels to illustrate the connections and relationships among the collected data (Van Eck and Waltman, 2014). The network links indicate the relationships between elements, while clusters are represented by different colors.

3. Findings

In this study, the first step involved filtering publications from the Web of Science database that included the keyword "Green BIM" and fell under the subject areas of "Construction Building Technology," "Architecture," or "Urban Studies." A total of 252 publications were selected for analysis. The study examined various aspects of these publications, including their publication and citation numbers over the years, the research areas they covered beyond the core subjects, document types, publication titles, publication numbers by countries, authorship and co-authorship patterns, publication numbers and citations by universities, and keyword analyses.

3.1. NUMBER OF PUBLICATIONS AND CITATIONS BY YEAR

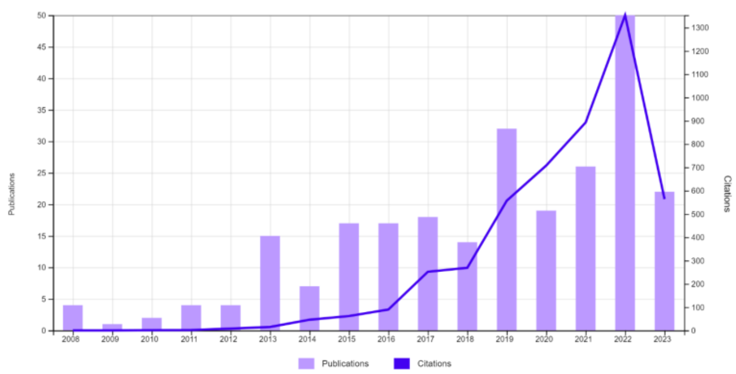

Figure 2: Number of publications and citations by years

Figure 2 illustrates the publication and citation trends of 252 publications over the years. The first publication in this dataset was recorded in 2008. Between 2008 and 2023, the year with the highest number of publications was 2022, totaling 50 publications. While there were occasional fluctuations in the number of articles in certain years, it appears that there has been a consistent upward trend in research activities related to this subject, particularly between 2020 and 2022. As of July 2023, the research conducted in 2023 was approximately half of the previous year's output. Citations express the scientific impact of an article among all times (Guo et al., 2019). When figure 2 is examined, it is seen that citations for publications has increased since 2010. The fastest increase was experienced between 2021-2022.

3.2. RESEARCH AREAS

All publications were filtered to focus on "Construction Building Technology," "Architecture," or "Urban Studies." However, it was observed that some publications also fell under different subject areas apart from these three categories. Table 1 provides a breakdown of these additional fields, which include engineering, science technology, energy fuels, environmental sciences ecology, materials science, computer science, and educational research.

TABLE 1: Research areas of the publications with record counts and percentages

Research Areas	Record Count	Percentage
Construction Building Technology	203	80.556%
Engineering	140	55.556%
Architecture	51	20.238%
Science Technology	37	14.683%
Energy Fuels	36	14.286%
Environmental Sciences Ecology	17	6.746%
Urban Studies	13	5.159%
Materials Science	7	2.778%
Computer Science	6	2.381%
Educational Research	5	1.984%

3.3. DOCUMENT TYPES

The document types available in the Web of Science are categorized into seven sub-titles: articles, proceedings papers, review articles, early access, book chapters, art exhibit reviews, and editorial materials. Based on Table 2, the predominant document type among the 252 analyzed publications was "articles" (62.302% rate, with 157 articles).

TABLE 2: Document types of the publications with record counts and percentages

Document Types	Record Count	Percentage
Articles	157	62.302%
Proceedings Papers	74	29.365%
Review Articles	20	7.937%
Early Access	5	1.984%
Book Chapters	2	0.794%
Art Exhibit Review	1	0.397%
Editorial Material	1	0.397%

3.4. PUBLICATION TITLES

As evident from the document type analysis, most publications are in the form of articles. This observation is further supported by Table 3, which lists the top 10 publication titles based on record counts, and all of them are journals. Among the publications related to "Construction Building Technology," "Architecture," or "Urban Studies" with the topic "Green BIM," Buildings Journal holds the first position with 30 publications (11.905% rate), publishing the most articles in this research area.

TABLE 3*:* Top ten publication titles with the most record counts.

Publication Titles	Record Count	Percentage
Buildings	30	11.905%
Automation In Construction	19	7.540%
Energy and Buildings	17	6.746%
Journal Of Green Building	17	6.746%
Building and Environment	14	5.556%
Sustainable Cities and Society	12	4.762%
Applied Mechanics and Materials	11	4.365%
Journal of Building Engineering	9	3.571%
Frontiers of Green Building Materials and Civil Engineering	8	3.175%
Procedia Engineering	7	2.778%

3.5. NUMBER OF PUBLICATIONS BY COUNTRY

Figure 3 shows the distribution of 252 publications, according to the top 10 countries in which they were published. According to the data obtained, China (83 publications) is in the first place among the countries with the highest number of publications. After China, USA (41 publications), Malaysia (23), England (21), Australia (20), Italy (12), Singapore (11), Canada (10), South Korea (8) and Taiwan (7) follows the graphic.

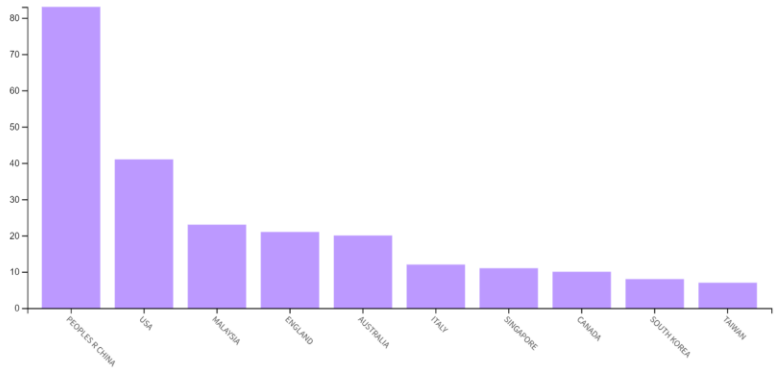

Figure 3: Number of publications by countries

3.6. AUTHOR AND CO-AUTHORSHIP ANALYSIS

As a result, out of 748 authors, 16 authors met this criterion. Table 4 displays the list of authors who have conducted research on the topic of "Green BIM" within the fields of "Construction Building Technology," "Architecture," or "Urban Studies." According to the table, the top five authors are Tang I. (with 7 publications and 162 citations), Xue P. (with 6 publications and 61 citations), Seghier T.E. (with 5 publications and 37 citations), Lim Y. (with 5 publications and 40 citations), and Yang T. (with 4 publications and 42 citations).

Figure 4 showcases a co-authorship network that depicts the collaborations among authors. The lines connecting author names represent the connections and collaborative relationships between authors (Van Eck and Waltman, 2010). The table reveals the existence of four co-authorship clusters, involving 16 authors. Notably, the table highlights the active networks of collaborations among authors such as Seghier T. E., Lim Y., and Ahmad M. H.; Zhang X., Tang I., Yang T., Shen J., and Xue P.; as well as Xue P., Fan C., and Chong A., Xu W.

Figure 5 visually illustrates the most productive years of the authors. According to the figure, Lim Y. and Fan C. are the authors with the most recent publications, suggesting their current high level of productivity in the field.

TABLE 4: 16 authors' document numbers and citations

Author	Documents	Citations
Tang, Ilewellyn	7	162
Xue, Peng	6	61
Seghier, Taki Eddine	5	37
Lim, Yaik-Wah	5	40
Yang, Tong	4	42
Fan, Cheng	4	56
Chan, Daniel W. M.	4	110
Wu, Zezhou	4	34
Shen, Jingchun	3	16
Zhang, Xingxing	3	16
Ahmad, Mohd Hamdan	3	36
Chong, Adrian	3	56
Xu, Weili	3	39
Azhar, Salman	3	332
Jalaei, Farzad	3	285
Kamaruzzaman, Syahrul Nizam	3	27

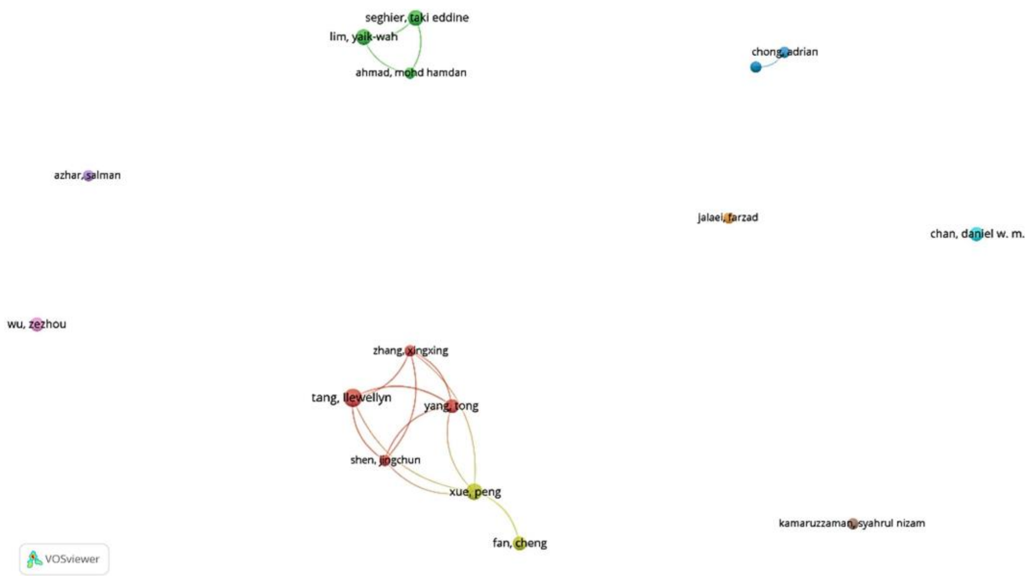

Figure 4: Co-authorship network / author collaboration

Figure 5: The most productive years of the authors

3.7. NUMBER OF DOCUMENTS AND CITATIONS BY UNIVERSITIES

Table 5 presents the universities where the filtered publications were produced, and only those with at least 5 publications are included. Out of a total of 322 organizations, 10 universities meet this publication threshold.

TABLE 5: Number of publications and citations by universities

Organization	Documents	Citations
Shenzhen University	12	113
Hong Kong Polytechnic University	11	762
National University of Singapore	7	332
Politecnico di Milano	7	41
Beijing University of Technology	6	61
Tongji University	6	314
Universiti Teknologi Malaysia	6	29
Southeast University	5	56
University of Hong Kong	5	59
University of Malaya	5	43

3.8. KEYWORD ANALYSIS

Keywords play a vital role in reflecting the core content of a publication (Xiang et al., 2017). In this study, the keywords were extracted by analyzing the content of the 252 publications using the co-occurrence option within the

VOSviewer. Co-occurrence refers to the shared existence or proximity of similar keywords (Lozano et al., 2019).

In this research, a minimum keyword repetition of three occurrences was established. Out of a total of 778 keywords, 56 keywords met this threshold. By applying the co-occurrence option and considering the frequency of their appearances, 49 keywords were identified. These 49 keywords were then classified into 9 distinct clusters by the VOSviewer program, based on their relationships within the publications. Each cluster is visually represented with a different color in Figure 6.

Cluster 1 is shown in red in Figure 6. In the cluster there are 10 keywords including buildings, built environment, citespace, construction industry, digital twin, gis, lidar, literature review, post-occupancy evaluation, urban planning. This cluster can be summarized under the title of urban studies. Sustainability assessment methods play an important role in identifying critical areas for both the environmental performance of buildings and the wider built environment, as well as socio-economic deficiencies at the urban scale (Salati, Bragança, Mateus, 2022). Sustainability initiatives that were originally centered on building-scale developments have progressively shifted towards encompassing larger urban-scale developments (Sharifi and Murayama, 2013).

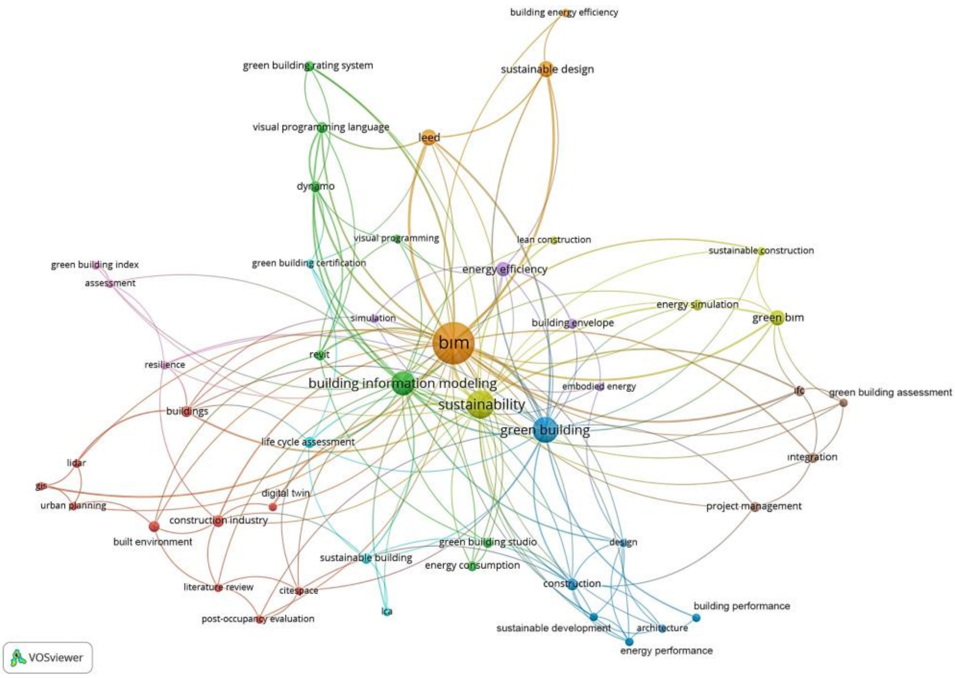

Figure 6: Keyword network analysis

Cluster 2 is represented with 8 keywords in green. These keywords are building information modelling, dynamo, energy consumption, green building rating system, Green Building Studio, Revit, visual programming, visual programming language. Cluster 2 is titled as visual programming. While visual programming has found widespread adoption in various disciplines, its significant role as a supplementary tool for three-dimensional modeling programs in the architecture, engineering, and construction industry has only emerged relatively recently (Kensek, 2015). Visual programming languages such as Dynamo employ graphical elements to construct software programs.

There are 7 keywords in Cluster 3, shown in blue. These keywords are architecture, building performance, construction, design, energy performance, green building and sustainable development. This cluster can be examined under the title of design & construction. BIM is suggested as a means to enable and streamline an integrated approach to project flow and delivery by employing collaboratively used, semantically rich 3D digital building models throughout all stages of the project and building life-cycle (Xu, Ma, Ding, 2014). Embracing the object-oriented concept, BIM enhances information management efficiency during the building life-cycle (Zhang and Hu, 2011). Moreover, BIM offers the capability to visualize and analyze construction projects with a near-real-life level of accuracy (Xu, Ma, Ding, 2014).

Cluster 4 is identified in yellow with 5 keywords. The cluster containing the keywords energy simulation, green BIM, lean construction, sustainability, sustainable construction is summarized under the title of sustainability. The primary objective of sustainable construction is to minimize energy consumption during both construction and operation phases while simultaneously preserving the environment (Hamraie, 2017). This approach leads to buildings that offer a high-quality living environment, maintain ecological harmony with nature, incorporate eco-friendly utilities, and effectively address energy and transportation challenges (Tetior, 2003).

Cluster 5 is shown with purple in Figure 6. There are 4 keywords in the cluster: building envelope, embodied energy, energy efficiency and simulation. This cluster can be titled with energy efficiency. BIM and sustainability share a common goal of developing efficient and innovative architectural and engineering solutions while safeguarding the natural environment and ecosystems (Carvalho, Bragança, Mateus, 2020). BIM facilitates the integration of sustainable measures throughout the project by enabling the consolidation and organization of multi-disciplinary information into a unified model (Wong and Kuan, 2014).

In Cluster 6, 4 keywords are expressed with light blue. The cluster containing the keywords green building certification, lca, life cycle assessment and sustainable building can be analyzed under the title of life cycle assessment. Life Cycle Assessment (LCA) serves as an appropriate approach for evaluating environmental performance. Integrating both LCA and BIM in the early stages of the decision-making process is essential to attain a comprehensive project overview, encompassing environmental criteria right from the project's inception (Antón and Díaz, 2014).

Cluster 7 consists of 4 keywords shown in orange. These keywords are BIM, building energy efficiency, leed, sustainable design. Cluster 7 is expressed with green BIM. Green BIM underscores the significance and function of BIM technology in the planning and construction of environmentally sustainable buildings. It establishes a standardized framework for the decision-making process and offers methodologies to enhance the eco-friendly performance of buildings (Liu and Wang, 2022).

Cluster 8 is expressed by 4 keywords in brown. In Figure 6, there are the words green building assessment, ifc, integration and project management in this cluster. This cluster is referred to project management as a title. BIM facilitates the establishment of a shared language and seamless integration among all stakeholders and divisions involved in a project, effectively transforming them into a cohesive and unified team (Rokooei, 2015). The principles of BIM align harmoniously with integrated project delivery systems, as it effectively merges diverse disciplines through robust communication, assesses project systems for constructability, provides real-time cost and time estimations through quantity takeoffs, offers a comprehensive visualization of projects, and fosters the development of collaborative teams (Kocakaya, Namlı, Işıkdağ, 2019).

Cluster 9 is shown in pink in Figure 6. The cluster includes the keywords assessment, green building index and resilience. Cluster 9 is expressed with green building assessment as a title. To evaluate the sustainability achievements of a green building project effectively, there is a requirement for assessment tools that designers can utilize to anticipate and assess building performances (Lim et. al., 2016). Through predictive assessments of building performance, decision-makers can devise strategies and methods that enhance building performance in a more cost-effective manner (Akadiri, Chinyio, Olomolaiye, 2012).

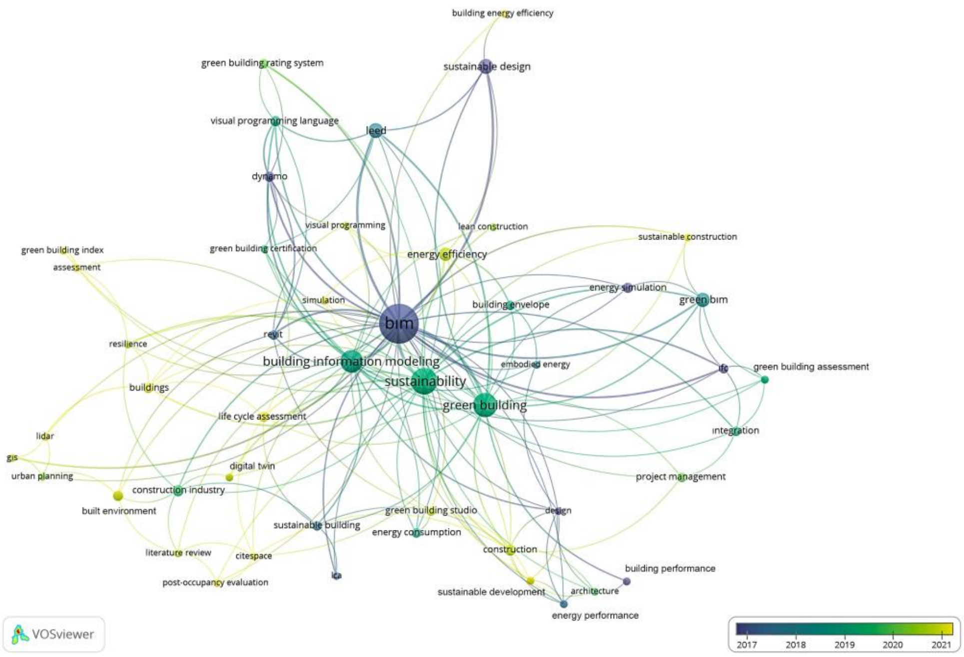

Figure 7: Change of the most used keywords over years

Figure 7 presents the visualization of the variations in the most frequently used keywords in publications over the years. The visualization is categorized into four different groups, denoted by the color groups of dark blue, turquoise, green, and yellow. These color groups serve as reference points for the categorization process.

Accordingly, specifying the keywords from the past to the present, the first category includes keywords such as BIM, sustainable design, leed, dynamo, energy simulation, embodied energy, ıfc, design, lca, revit, energy performance and building performance.

Second category consists of visual programming language, building envelope, green BIM, green building, sustainability, building information modelling, green building certification, integration, energy consumption and green building assessment.

In the third category, the keywords are; green building rating system, urban planning, construction industry, project management, architecture, and lean construction.

Keywords of the most recent publications include building energy efficiency, visual programming, energy efficiency, sustainable construction, construction, green building studio, citespace, literature review, green building index, assessment, resilience, buildings, simulation, life cycle assessment, lidar, GIS, post-occupancy evaluation, built environment, digital twin and sustainable development.

Analyzing the keywords in recent publications, it becomes evident that urban studies is the most prominent area associated with green BIM. This indicates that, unlike other academic research, there is a focus on prioritizing the implementation of green BIM at the urban scale. The most current keywords related to urban design include buildings, built environment, citespace, digital twin, GIS, LiDAR, literature review, and post-occupancy evaluation.

4. Results

The bibliometric analysis primarily concentrated on publications in the fields of construction building technology, architecture, and urban studies that contained the term "Green BIM." These chosen publications present an extensive analysis based on various criteria, including publication and citation years, research areas, document types, publication titles, publication numbers by countries, authorship and co-authorship patterns, publication numbers, as well as citation analyses by universities and keyword analyses. By consistently applying a specific search filter, the study successfully identified the most frequently cited publications released between 2017 and 2023, thereby providing insights into the prevailing trends and advancements in the domain. The results are as follows:

- Between 2008 and 2023, the year with the highest number of publications was 2022 and the period during which the number of publications experienced the most rapid growth was between 2021-2022. While there were occasional fluctuations in the number of articles in certain years, it appears that there has been a consistent upward trend in research activities related to this subject, particularly between 2020-2022. Moreover, citations for publications have increased since 2010. The fastest increase was experienced between 2021-2022. The year 2022 was the most cited year with 1353 citations.
- Other fields in which publications fall within the range of topics apart from architecture, construction building technology and urban studies are engineering, science technology, energy fuels, environmental sciences ecology, materials science, computer science, and educational research. It is possible to say that the publications are highly related to the engineering field apart from previously filtered research areas. This may help us interpret that technical studies have been carried out on the subject.
- The majority of the 252 analyzed publications are in the type of articles.

- According to the number of publications, all of the references are journal papers. This demonstrates the relevance of the topic.

- When the number of publications is analyzed by country, China has most of the studies in the researched subject.

- The most productive 5 authors from 2008-2023 in the studied field are Tang I., Seghier T.E., Lim Y. and Yang T. Four co-authorship clusters were identified with sixteen authors. Furthermore, the most cited author is Azhar S. Authors who have made the most recent publications include Lim Y. and Fan C. Especially the publications of these authors related to the subject can be examined.

- According to the number of documents, Hong Kong Polytechnic University, Politecnico Milano and Georgia Institute Technology are in the first three places.

- For keyword analysis, 49 keywords are divided into 9 clusters which reveals the headings: urban studies, visual programming, design & construction, sustainability, energy efficiency, Life Cycle Assessment (LCA), green BIM, project management, green building assessment.

- Keywords of the most recent publications are building energy efficiency, visual programming, energy efficiency, sustainable construction, construction, green building studio, citespace, literature review, green building index, assessment, resilience, buildings, simulation, life cycle assessment, lidar, gis, post-occupancy evaluation, built environment, digital twin, and sustainable development. Upon analyzing the keywords present in recent publications, it becomes apparent that urban studies stand out as the most dominant field in connection with green BIM. This situation highlights that, unlike other academic studies, priority is given to urban-scale applications of green BIM.

- Also, with urban scale studies in general, potential areas for academic studies include Life Cycle Assessment (LCA) and using BIM in the LEED certification process. Recently, due to the rapid development of information technologies, BIM is used in green building applications and current studies are carried out on these issues. However, academic studies on approaches are lacking to integrate Green BIM technology into sustainable building design and studies are needed on these issues. Presently, there is a discernible preference within the industry and prominent publications for technical studies, as generic investigations appear to have reached a state of saturation (Hosseini et. al., 2018; Hosseini et. al., 2018).

- Despite the valuable contributions of this study, there are certain limitations to acknowledge. The analysis relied on a dataset extracted from Web of Science, which may be influenced by the inherent limitations of the platform's publication coverage. Additionally, the literature review was confined to three primary research areas. To overcome these limitations, future research endeavors could explore data from diverse sources and employ a range of indicators to assess impact, quality, and interconnections within the literature.

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6.A.

VIRTUAL REALMS AND MULTIVERSE ENVIRONMENTS - II

THE VIRTUAL WAYS OF SETTLING DOWN: REINTERPRETING THE TRANSFORMATION OF SPACE IN METAVERSE

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Abstract. Metaverse has become a point of discussion in recent years, although the word 'metaverse' has been around for more than two decades. Consequently, metaverse platforms are growing in number and capacity, with the media feeding their popularity. Design in and of the metaverse is also the focus of architecture. As computational tools allow for visionary design that is difficult to build in real life, designers are inspired by the possibilities of the metaverse. However, the impact it has on the transformation of architectural space is seldom debated. As the boundary between physical and virtual spaces becomes less clear, the virtual spaces created in and for the metaverse will affect how humans live and shape their spaces. For this reason, it is necessary to reinterpret how we define spaces before creating computational means to make them. Focusing on one of the most vital spaces, the home, this study aims to draw attention to the act of 'building a home', in other words, 'settling down', which is still open to speculation in terms of architecture today. In order to question its reflections in the metaverse where virtual lands and houses are being sold, a two-part online workshop was conducted. The workshop included nine participants, who were mostly architecture students and graduates, and one with a social sciences background. The first part focused on theorizing settling down based on Heidegger's related terms of 'construction, dwelling and thinking' and the alternative ways of settling down throughout history, and its virtualization. The discussions centered on 'a new home' that the metaverse enabled people to build through familiar things they identified with. In the second part, participants asked whether the metaverse was a tool or the goal by working in groups to create their own ways of settling down in virtual space via the things they identified with being at home the most. In line with the increasing communication, interaction, and common life in the metaverse, the participants questioned this new life and redefined the act of 'settling down', where both construction and dwelling are reconciled, through mind maps and representations made possible by different techniques such as artificial intelligence-based image generation, designing inside game environments, and collages. They considered the metaverse as a source of inspiration to experience different spaces, access memories, and show their identities to the world.

Keywords: *metaverse, virtual space, settling down, vital.*

ملخص. لقد أصبح الميتافرس نقطة نقاش في السنوات الأخيرة، على الرغم من أن كلمة الميتافرس كانت موجودة منذ أكثر من عقدين من الزمن. ونتيجة لذلك، تتزايد منصات الميتافرس من حيث العدد والسعة، حيث تغذي وسائل الإعلام شعبيتها. التصميم في الميتافرس هو أيضًا محور الهندسة المعمارية. وبما أن الأدوات الحسابية تسمح بالتصميم الخيالي الذي يصعب بناؤه في الحياة الواقعية، فإن المصممين يلهمون إمكانيات الميتافرس. ومع ذلك، فإن تأثيرها على تحول الفراغ المعماري نادرا ما يتم مناقشته. نظرًا لأن الحدود بين المساحات المادية والافتراضية أصبحت أقل وضوحًا، فإن المساحات الافتراضية التي تم إنشاؤها في ومن أجل الميتافرس ستؤثر على كيفية عيش البشر وتشكيل مساحاتهم. لهذا السبب، من الضروري إعادة تفسير كيفية تعريفنا للمساحات قبل إنشاء وسائل حسابية لتصنيعها. من خلال التركيز على أحد أهم الفراغات الحيوية، وهو المنزل، تهدف هذه الدراسة إلى لفت الانتباه إلى فعل "بناء المنزل"، أو بمعنى آخر، "الاستقرار"، الذي لا يزال مفتوحًا للتخمين من حيث الهندسة المعمارية اليوم. من أجل التشكيك في انعكاساتها في عالم التحول حيث يتم بيع الأراضي والمنازل الافتراضية، تم إجراء ورشة عمل عبر الإنترنت من جزأين. ضمت الورشة تسعة مشاركين، معظمهم من طلاب وخريجي الهندسة المعمارية، وواحد ذو خلفية في العلوم الاجتماعية. ركز الجزء الأول على تنظير الاستقرار بناءً على مصطلحات هايدجر ذات الصلة بـ "البناء والمسكن والتفكير" والطرق البديلة للاستقرار عبر التاريخ وافتراضيته. ركزت المناقشات على "المنزل الجديد" الذي مكّن الميتافرس الأشخاص من بنائه من خلال الأشياء المألوفة التي تعرفوا عليها. في الجزء الثاني، تساءل المشاركون عما إذا كان الميتافرس أداة أم هدفًا من خلال العمل في مجموعات لإنشاء طرقهم الخاصة للاستقرار في الفراغ الافتراضي عبر الأشياء التي ميزوا وجودهم في المنزل أكثر من غيرها. تماشيًا مع زيادة التواصل والتفاعل والحياة المشتركة في عالم ما وراء البحار، شكك المشاركون في هذه الحياة الجديدة وأعادوا تعريف فعل "الاستقرار"، حيث يتم التوفيق بين كل من البناء والمسكن، من خلال الخرائط الذهنية والتمثيلات التي أصبحت ممكنة بفضل تقنيات مختلفة مثل إنشاء الصور المستندة إلى الذكاء الاصطناعي، والتصميم داخل بيئات الألعاب، والصور المجمعة. لقد اعتبروا الميتافيرس مصدرًا للإلهام لتجربة مساحات مختلفة والوصول إلى الذكريات وإظهار هوياتهم للعالم.

الكلمات المفتاحية: الميتافرس، الفراغ الافتراضي، الاستقرار، الحيوية.

1. Introduction

Despite the term "metaverse" being used for more than twenty years, it has only recently been a topic of controversy. As a result, the media is fueling the growth of the metaverse platforms in terms of both capacity and number. Architecture focuses on design both within and outside of the metaverse. Architectural design within the metaverse recreates real-life spaces or envisions entirely new environments that aim to transcend the limitations of the physical world. Designers work on bringing to life aesthetic and functional structures, blending artistic creativity with practical considerations. Regardless of the design, architecture plays a crucial role in creating immersive environments that users can inhabit and explore. Designers are motivated by the potential of the metaverse, as computational technologies enable visionary design that is challenging to build in reality. The effect it has on the modification of architectural space, however, is rarely questioned. The virtual places made in and for the metaverse will influence how people live and shape their environments as the line separating actual and virtual spaces blurs.

Contrasting perspectives on the role of architecture in the design of/for metaverse focus on whether the metaverse is another hoax or a fertile platform for architects. This study aims to take an objective view of the disparate criticisms and draw its own conclusions regarding the act of building and dwelling in the metaverse. A two-part online workshop was held to question the reflections of spatial transformation in the metaverse, where recent arguments focus on the economic implications. A young group of nine participants with mainly architectural backgrounds contributed their ideas and worked together to come up with a new understanding of home.

The first section of the workshop was devoted to theorizing about settling down based on Heidegger's "construction, dwelling, and thinking," as well as the various historical alternatives to settling down and its virtualization. Instead of academic resources, stories were used to expand the vision. Seemingly unrelated ideas were brought together by free association to build upon the existing discourse. The literature review makes up the conceptual framework of the workshop. At the end of the first section, the discussions focused on creating "a new home" in the metaverse using items that people were already familiar with. In the second section, participants developed their own means of settling down in virtual space while debating whether the metaverse was a tool or an outcome. Participants were asked to form groups based on the similarity of things they proposed that made them feel at home. Four groups used different design tools and visualization techniques to convey their idea of home in the metaverse. The tools ranged from prompt-based AI to hand sketches. In line with the theoretical and practical discussions, the participants underlined society, individuality, inspiration, memory, experience, and dynamism as the key concepts for settling down in the metaverse.

2. Theoretical Background

2.1. SETTLING DOWN

In architectural literature, the concept of "settling down" has long been an issue. Two English words are commonly used to describe “settling down”: house and home. According to Rykwert (1991), the difference between these two words is as follows: “*Home is where one starts from. That much is obvious. A home is not the same as a house, which is why we need two different words. Does a home need to be anything built at all, any fabric? I think not. Home could just be a hearth, a fire on the bare ground by any human lair. That may well be the one thing nobody can quite do without: a fireplace, some focus. After all, if a home had no focus, you could not start from it.*”

Today, while the construction industry deals directly with the house, architecture is about both the house and the home because of its strong relationship with the user. Heidegger pointed out that dwelling equates with the actions of building and thinking. For him, dwelling required being in touch with the world, like a gardener when working the land, so the dweller could be in peaceful reconciliation with earth, sky, divinities, and death. However, this direct connection between the land and the man in architectural history has been broken with the modern architect’s approach to design and their works. Specialization has separated building from dwelling (Sharr, 2008). Although architects like Loos did not have such an attitude, modern architecture came to the fore by reducing three-dimensional space to two dimensions, a kind of visual art rather than the experience of space. Le Corbusier's buildings and their photographs published in magazines contributed greatly to this. It ultimately caused the architect himself to practice architecture at the drawing table, away from the construction site, let alone the experience (Colomina, 2020). On the other hand, the houses they designed included many architectural strategies aimed at the personalities of their (probably prosperous) users, so they became homes. Then, what about the working-class’ homes? It was obviously houses instead of them under the effect of the state, with a capitalist economy, as homogeneous architectural volumes of a unit in the periphery. At that time, the role of the architect became more dominant as a designer because s/he designed only for the ideal worker (Lefebvre, 2016). Moreover, for Colomina (2020), visibility was one of the most important issues of modern architecture. In this manner, Loos and Corbusier approached it differently. While Loos believed that a house should not reveal any secrets about the interior from the exterior, Corbusier not only increased the permeability between the inside and the outside but was also content to have the photographs of his interiors printed in the magazines of the period. So, architecture itself became meaningful with the mass media.

Other than the architectural literature, looking at “settling down” from the outside will be fruitful in revealing its relationship with human nature. According to Tournier (2022), thought is processed through a number of key concepts, and these concepts are composed of positive but opposite pairs. In the pair of "nomadic and settled," the author discusses the origins of human history. Cain settles down, engaging in agriculture, while Abel leads a nomadic life, tending to herds. A conflict arises when one of Abel's animals enters Cain's crops, leading to Abel's murder. As a punishment, God makes Cain a nomad like his brother. Cain eventually stops and finds the first city, transitioning from a farmer to an architect. Secondly, the "cellar and attic" pair symbolizes opposite ends of a house, one facing the earth, the other the sky, both dark. Influenced by Baudelaire, the author defines the cellar as a space for growth, while the attic is a storage space associated with memory, a kind of retrospective death. Lastly, the author explores "memory and habit" through Bergson's ideas. Memory is linked to the soul, as Proust's madeleine example shows. Habit, on the other hand, is physical, involving accumulated actions like walking, reading, and playing tennis, reflecting the brain's use of past information in the present.

In "The Book of Human Emotions", Smith (2022) explores the concept of "feeling at home," which is relevant to this study's context. The author illustrates the feeling using poet John Clare's story of escaping a mental hospital to return home to Mary Joyce. Clare's arduous journey ended with the heartbreaking discovery that Joyce had passed away. This experience led Clare to describe the profound loneliness of feeling homeless within one's own home. As evident from these examples, even though the direct connection between dwelling and building has been broken in the modern era, dwelling still maintains a significant association with physical construction. This becomes particularly relevant in this study’s investigation as it contemplates the feasibility of re-establishing dwelling in virtual space.

2.2. METAVERSE

Metaverse was first coined by Neal Stephenson in his novel “Snow Crash” (1992). However, it was not Stephenson who imagined the virtual world as it is. The inspiration for Metaverse came from Vernor Vinge’s “True Names” (1981) and William Gibson’s novels, such as the famous “Neuromancer”, both of whom owed their works to Morton Heilig’s Sensorama Machine (1962) (Zuckerman, 2021). Though Facebook became mainstream with its rebranding as Meta and Mark Zuckerberg announcing the Metaverse, attempts to create one started more than two decades ago. OZ Virtual, Netscape's Blaxxun and the much more popular Second Life can be categorized as metaverses. What makes a platform metaverse and where these metaverses stand in different categories can be explained by the scenarios envisioned during the Metaverse Roadmap Summit in 2006.

Based on the Metaverse Roadmap Summit (2007), there are four metaverse scenarios: virtual worlds, mirror worlds, augmented reality, and lifelogging. The scenarios are situated on two axes: external-to-intimate and augmentation-to-simulation. External focuses on technologies about the metaverse as a whole, an environment, whereas intimate technologies are about individual things like identity, appearance, and such. Augmented technologies add to the system; they expand the limits of our experience. Simulation reflects reality and what could happen under different parameters and behaviors. Simulation and intimate technologies make up virtual worlds, while simulation and external technologies construct mirror worlds. Today, digital twins are a more widespread use of the concept of mirror worlds. Augmented reality, on the other hand, is created by augmentation and external technologies. Lastly, augmentation supported by intimate technologies sets up lifelogging.

Matthew Ball (2022) summarizes what the metaverse is and is not based on the examples and discourse accumulated around the term. According to Ball, the metaverse is a fully functioning economy with interoperability and a sense of individual presence. The experience spans the digital and physical worlds, with many participants, synchronously and live, and it is continuous. Metaverse is not a digital and virtual economy, a virtual space, a new UGC platform, a virtual theme park, a new app store, virtual reality, a virtual world, or a game. Metaverse is at the center of the idea that Web3 is coming. Web2, which we are familiar with today, has been centralized where data belongs to corporations. Traditional currencies are the medium of transactions. However, Web3 claims to be decentralized, and the owner of the data is the one that creates it. Cryptocurrencies are preferred. Popular platforms today are situated on a blockchain-based - traditional transactions, centralized - decentralized spectrum. Meta is a centralized, blockchain-based project, while Decentraland is its decentralized associate, as its name suggests. Popular "game" platforms such as Grand Theft Auto, Minecraft, and Roblox have traditional economies and centralized systems.

Despite the allure of the interconnected worlds of the metaverse, the criticism is harsh and comes from important names in the field. Ethan Zuckerman (2021), one of the makers of the first metaverses by trying to recreate the vision of Neal Stephenson, picks on the ignored yet dire parts of metaverse platforms. As he mentions, Stephenson's metaverse was a dystopia. However, technologists have a tendency to look at anything new and exciting as something good. What is envisioned as the metaverse, a vast, democratic environment that enhances life, crashes soon. Online platforms turn into places of abuse and consumerism. Although graphics technology has advanced a lot in the last decade, metaverse graphics are slightly better than they were in the late 1990s and early 2000s.

Futurist Jamais Cascio (2007) brings forth Kurzweil's Singularity as a plan for the metaverse's future. He suggests that an Open Singularity that is transparent and based on open-source solutions will create a democratic platform. While his vision might be true and the ideal way of looking at the metaverse, reality might be different. Humans, who are making and using the metaverse, will shape its essence. It might be a space to escape from reality, a place for realizing our wildest dreams that we cannot in the physical world, an arena for being someone else. It might just become an escape from life instead of augmenting and making our lives easier. Slavoj Zizek (2022) puts it clearly in words:

"Metaverse will act as a virtual space beyond (meta) our fractured and hurtful reality, a virtual space in which we will smoothly interact through our avatars, with elements of augmented reality (reality overlaid with digital signs). It will thus be nothing less than metaphysics actualised: a metaphysical space fully subsuming reality which we will be allowed to enter in fragments only insofar as it will be overlaid by digital guidelines manipulating our perception and intervention. And the catch is that we will get a commons which is privately owned, with a private feudal lord overseeing and regulating our interaction."

One of the prominent names in designing the metaverse, Schumacher (2022) believes that architects will be the primary creators of it. Following the Liberland designed by Zaha Hadid Architects (ZHA) and the works of graduate students at AADRL, he proposes twelve theses that correlate to the metaverse ideals. However, the speculation still falls short in terms of spatial transformation. The examples are reflective of the ZHA style. It is not convincing to design a metaverse out of a disputed real land in terms of freedom and equality. Form is the prevalent factor in designing for the metaverse. How the space actually is must be the question. For this reason, architecture in/for the metaverse is necessary to analyze. Even though the concepts and ideas behind the metaverse architecture are exciting, the design products only seem to be fluid forms and interactive screens. In order to develop meaningful design that will shape the future, designers must consider criticism. Questions for designing in and for the metaverse while taking a critical stance have been identified as follows:

- Who will design the metaverse? Who will be responsible for its ever-developing design?
- Will there be laws and regulations? Will it be divided into zones?
- Can it be open-source, ensuring democratization?

- Will there be limits to buildings, structures, materials, costs? How will they transform? Will/Should there be real world counterparts?
- Is it possible to create instead of exhibit, produce instead of consume?

3. Methodology

Combining the speculative issue of “settling down” and metaverse hype, this study evokes a discussion environment on the potential of establishing a home in virtual space. The purpose of this environment is to reveal how people can participate in the criticism and reinterpretation of the spatial transformation that comes with designing for the metaverse.

The use of workshops as a research method is one of the qualitative methods suitable for the study of domain-related cases. According to Ørngreen and Levinsen (2017), workshops are successful in revealing what is not clearly revealed between the coordinator and the participants before starting the workshop itself, as the coordinators of the workshop bring together a group of participants and help them brainstorm creatively in order to solve an ill-defined or complex problem. Thus, workshops are kinds of facilitators to catch the meaning behind the real. In addition, workshops held digitally via video conferencing provide convenience in terms of accessing many participants who are far from each other and subjecting them to the same space experience virtually (Hedestig and Kaptelinin, 2005; Ørngreen and Levinsen, 2017). In this respect, this space is the “third room” that allows the common experiences of the participants (Levinsen, Ørngreen & Buhl, 2013). The third room in this study made it possible for both the coordinators and the participants to rethink the virtual space, and to produce ideas about it, with some clues from the literature about what space is. By this way, both the participants were given a critical perspective, and the coordinators were able to reveal the similarities and differences in the perspectives of the participants.

The material of this study is the workshop titled “Virtual Ways of Settling Down” conducted by the authors within the scope of an organization called Good Design Izmir. The organization, located in Izmir, makes an open call to organize activities such as workshops, seminars, and exhibitions around a selected theme every year. The theme of the event in 2022 was determined as "vital". The open call focused on the global climate crisis that emerged as a result of the irreparable damage done by humanity to the sustainable mechanisms of nature and the humanitarian crisis that emerged through migrations and wars. It was also stated that in this geographical and demographic crisis environment, the regenerative and reparative aspect of design was needed.

The relationship of the workshop “Virtual Ways of Settling Down” with the event theme was built on humanitarian crises, and the conceptual framework was built on the issues of "life, home, and belonging". Based on this speculative subject, the potential of using workshops to move these issues to the "virtual space", which has increased visibility with COVID-19, and to discuss how and in what ways this will be possible in terms of design was explored.

The call for the workshop was announced on Good Design Izmir's website and social media accounts (Figure 1). The aim of the workshop in the call was stated as: "*...to draw attention to the act of "building a nest", which is still open to speculation in terms of architecture, and to seek its reflections in the virtual environment when virtual lands and houses are started to be bought and sold. In line with the increasing symbiosis, communication, and interaction in this environment, the participants will question this new life and redefine the act of "building a new home", where both construction and dwelling are reconciled, through a designated virtual platform.*" The target audience of the workshop was defined as "*anyone who is curious about and criticizes life changing with technology and wants to design life in the virtual environment*". The language of the workshop was Turkish.

Figure 1. Call for the workshop.

Seventeen people applied to the open call, but the number of people actively participating in the workshop was nine. Three of them were Bachelor of Architecture graduates (P1, P2 and P3), four were undergraduate architecture students (P4, P5, P6 and P7), one was a student of the History of Architecture Master's Program (P8), and one was a web content manager (P9). The native language of all the participants was Turkish. The workshop program was planned as three sessions: the first session on October 8 (a) and the second session on October 9 (b) for four hours, and the last session on October 13 (c) for two hours:

(a) In the first session, the participants introduced themselves and their interest in the subject, the coordinators made their presentations to reveal the conceptual framework of the workshop (which is mentioned in the previous section). The participants expanded the discussion by bringing their own thoughts to the agenda. Following the discussions, the participants were asked to look for an answer to the following question from within the conceptual background: "*If you were to continue your life in the metaverse from now on, what would you take with you from your home to this world?*" This question was important in terms of determining what it was that would make the participants feel at home individually. The participants brought these findings and related issues together by diagramming on Mural.

(b) The second session started with the participants presenting their approach to the issue along with their diagrams. Similar or opposite approaches that were speaking the same language in these presentations were grouped by the participants and the coordinators. A total of four groups were formed, with a maximum of three people. Then, the groups were given time to brainstorm about their spatial ideas in the breakout rooms, while they were asked to diagrammatize their thoughts through conceptual maps on Mural, and they were encouraged to start their spatial productions. At the end of the session, the groups discussed their views all together. Participants contributed intellectually to each other.

(c) The third session took place four days after the second session, during which the participants were expected to complete their group work and turn it into a presentation. Their presentations were discussed and evaluated together with the guests invited to the final review.

In addition, the digital presentation of the final products of the workshop was exhibited by Good Design Izmir on October 15, 2022, at the Atlas Pavilion in Izmir Kültürpark. Figure 2 summarizes the outline of the workshop.

4. Results

Session one of the workshops focused on the discussions and what the participants took away from them. According to the discussions, home was associated with identity, belonging, memory, privacy, and hearth, while virtual was associated with common life, belonging, security, solidarity, property, and identity. Participants were asked to come up with three things that they identified with being (at) home. Things proposed by participants were mostly intangible (experiencing, sharing, thinking, drawing, watching), a couple of tangible things like photos and collections, also focused on nature with keywords like green, sea, and sky. The participants worked simultaneously on Mural, and related keywords were linked and grouped together with moderators' feedback. Two major themes regarding what makes a space home were found after the grouping of keywords (Figure 3):

- Where I can be with myself,
- What I am surrounded with.

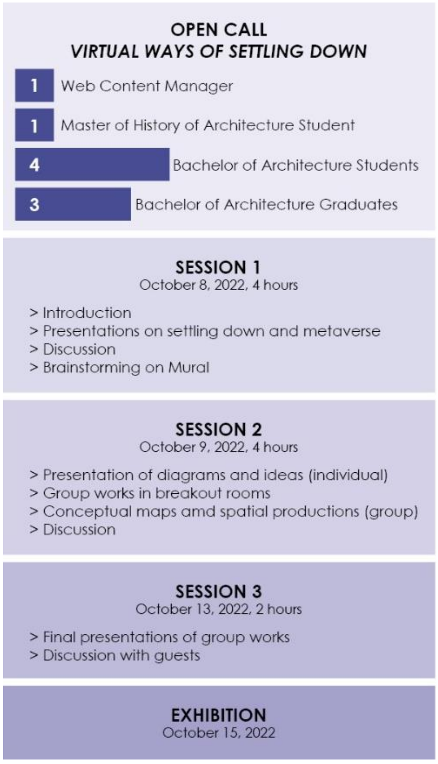

Figure 2. Workshop outline.

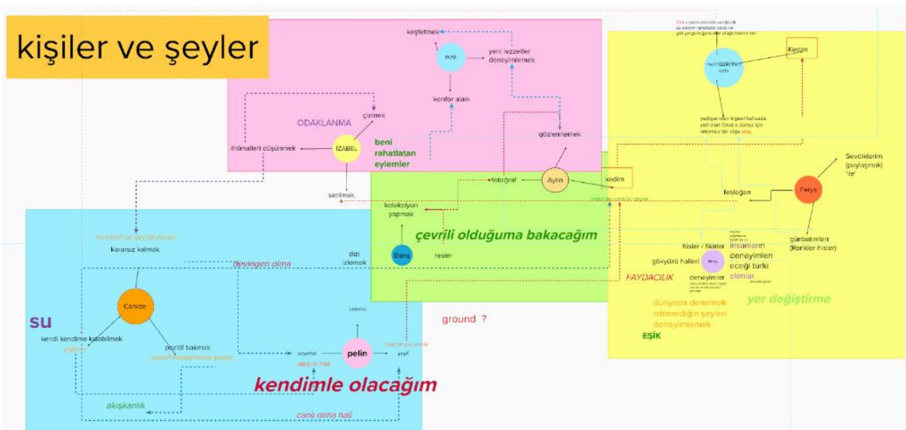

Figure 3. People and things, participants working process.

Groups were formed according to the similarity of the views each participant had regarding the subject. Group 1 (P1, P8 and P9) focused on experiences that people couldn't have in the physical world. They underlined the value of sharing in the metaverse. Also, their emphasis was on emotions and abstract values. Group 2 (P2 and P4) looked at the dynamism of the metaverse where they could travel, be on their own, and also experience some kind of natural effect. Group 3 (P5 and P6) thought about the things that they could do in the metaverse that would remind them of home. Thus, their focus was on the memory constituted by exploration. Group 4 (P3 and P7) focused on an outward reflection where they would draw inspiration from other things like collections and photographs shared by other people and by themselves (Figure 4).

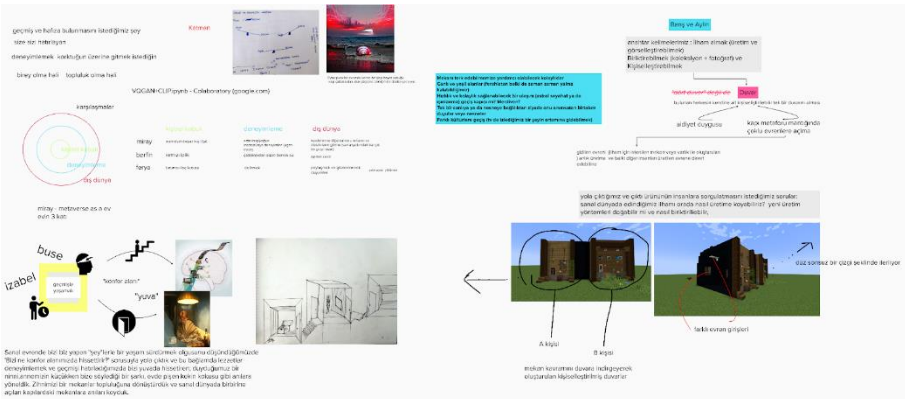

Figure 4. Group works in progress.

Groups were asked to come up with their idea of home in the metaverse. They were allowed to use whichever representation technique they found suitable for their ideas. However, they were encouraged to use digital tools. Group 1 reimagined the home in the metaverse using prompt-based AI tools. They interpreted settling down as having a three-layered structure: personal layer, experience layer, and the outer world. Their vision of home in the metaverse was supported by AI generated images through poems. The personal layer was interpreted by each individual differently. This was a bird feather for person A, a red thread for person B, and an orange pill box for person C. The experience layer allowed people to experience things they could not in the real world, such as flying without any apparatus or vehicle, or going crazy. The outer world was where we could see and be with other people, sharing and observing. Group 1 used the VQGAN+CLIP model for creating their poem-based metaverse visions (Figure 5). Their preferred method also underlines the human-machine partnership that is core to decentralized platforms.

Figure 5. Group 1 final works.

Group 2 focused on the dynamism that virtual worlds allow people to experience. They interpreted home as not one thing to depend on but many things that remind us of it. These things could be experienced through travel in the metaverse. Being able to travel between virtual spaces underlines the fast and easy means of transport Metaverse offers. How people leave and enter a space was a question they were concerned with. Could it be something familiar, like a door or a staircase? Group 2 also focused on the way nature was related to feeling at home. They tried to balance nature and the real world in the metaverse by asking how we could be with nature without ignoring the world. Their keywords were green and water, underground and sky. According to this group, home is one's own self. Green and lively spaces in the metaverse could potentially comfort us and let us be on our own. They modeled their ideas in Sketchup, and used Lumion and collage-making techniques in post-processing (Figure 6 and Figure 7).

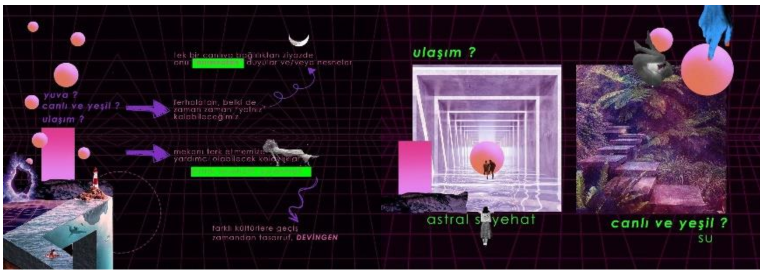

Figure 6. Group 2 final work.

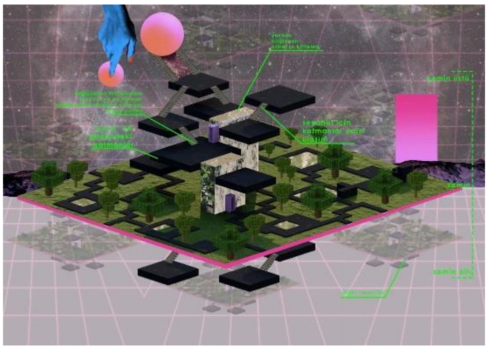

Figure 7. Group 2 final work.

Group 3 centered the home in the metaverse on memory. Their idea of home was equivalent to comfort. They questioned what made them feel in their comfort zone. In this context, the flavors they experienced, and remembering the past made them feel at home. They turned to memories such as a lullaby they heard, a song their mother sang to them when they were little, and the smell of home-baked cake. They imagined their minds as a community of spaces and put memories in the spaces that were open to each other in the virtual world. Their keywords were memory box, doors in our minds, and comfort towards memories. The spatial orientation could be both linear and cyclical, based on the memory palace they built. Group 3 used hand sketches and collages to represent their ideas (Figure 8).

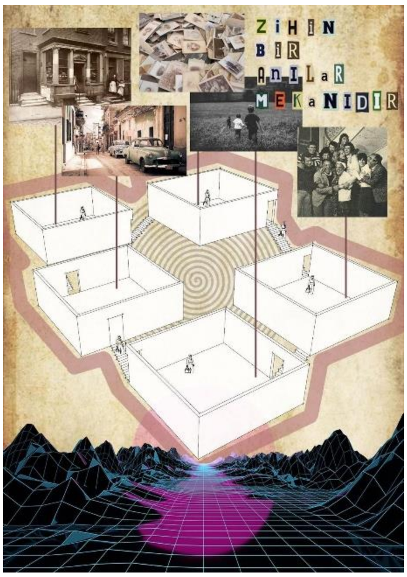

Figure 8. Group 3 final work.

Group 4 started off by questioning how they could create in/inspire from the virtual world. Creating something in the virtual world was what they mostly focused on. They wanted to investigate the way production and collection were made. They deconstructed the idea of four walls. Walls are familiar to us, but instead of walls enclosing space, there is the concept of a wall that can be personalized. These walls reflect each individual's personality. There is an abstract world behind the wall for inspiration. There is an opportunity to travel between different worlds and invite others to our world. These worlds could be created in mere moments. Their keywords were inspiration, collection, personalization, door as a metaphor for different worlds, and wall as a reflection of one's identity. They developed their ideas in Minecraft, which is a sandbox game that is considered a kind of metaverse. They used collage techniques as post-processing (Figure 9 and Figure 10).

Figure 9. Group 4 final work.

Figure 10. Group 4 final work.

5. Conclusion

In the light of what the participants came up with, the workshop results showed that home/settling down is a crucial and difficult part of designing in/for the metaverse. Each person has a distinct idea of home, despite the similar nature of their ideas. However, bringing together the related ideas brought about inspiring solutions. Table 1 shows the key points for each group in terms of the design idea, interpretation of the home and tools. Each group focused on different aspects of home, yet the consensus is that experience, identity, and memory are three key concepts. The ideas were interrelations of inner and outer worlds: being a person within a society, traveling individually, memories connected to each other, doors opening to other worlds.

As the workshop was conducted for a limited time, participants were allowed to use any tool that they were comfortable with. Along with traditional sketching and modeling, participants were enthusiastic about producing AI-generated images and using games to create. This supports the idea that AI-based tools and game engines will be the dominant tools of metaverse design. Discussing the home issue in the context of the metaverse is also a reaction to Colomina's claim that architecture deals with outdated mass media. Today, architecture means searching for possibilities of existence through different means of communication.

TABLE 1. Group works summarized.

	Group 1	Group 2	Group 3	Group 4
Design idea	Being a person and being a society	Dynamism, travel, individuality	Memory boxes as community of spaces	Deconstructing walls and doors
Conceptual pairs	Person / Society	Travel / Individualism	Memory / Community	Doors / Walls
Interpretation of home	Three-layer structure: Personal layer, experience layer, outer world	Things that remind us of home. One’s own self.	Memory of things that comfort the person.	Inspiration and personalization
Tools	VQGAN+CLIP	SketchUp + Lumion	Collages, sketches	Minecraft, collages

The experience of conducting an online workshop where collaboration was encouraged helped both participants and coordinators uncover new and exciting ideas. Making a collaborative workshop was also a simulation of what the metaverse aims to be: a live environment where each individual adds their input to make something larger than the sum. Workshops, in essence, rarely produce finished products; their outcomes are more open-ended and speculative. It is not possible to generalize or make definitive inferences from a small group, but this study may be an inspiration for architects who will design the metaverse by looking at the problem from architecture's unresolved debates on space. By questioning the ways of settling down in virtual space, the workshop itself gains its push from being speculative. The third room, as mentioned in the methodology, allowed participants and coordinators to rethink the virtual space and idea of home, stimulating a critical perspective in participants and helping coordinators rethink and reveal similar and contrasting perspectives about the issue. The home itself is a complex issue on its own, thinking about it together with the metaverse and even bringing together two things that are not so easy to come together causes the matter to become even more complex and dimensional. Not forgetting the criticism regarding the metaverse, as this technology seems inevitable whether it stays in its current form or transforms into something else, architects and designers need to rethink spatial transformation and how they will contribute positively to the change.

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VISUAL APPROACHES ON SPATIAL THINKING

User Interface Metaphors

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Abstract. This study explores the link between the development of spatial ideas and the use of the user interface in the digital tools that support it, aiming to follow both mental and digital navigation in the design process. Spatial metaphors at the focus of this exploration were evaluated through spatial interface functions, which provide designers with the ability to manipulate objects and their environments in a 3D environment. In the empirical case study conducted with 4 designers, two different scenarios were used using the same materials. Different approaches to the visual expression of spatial metaphors were compared over these two scenarios. In the first scenario with two participants, the participants perform the tasks through sketches and diagrams. In the other scenario, participants complete the same tasks during the 3D modelling process. These outputs, which are a visual manifestation of the designer's spatial thinking, are expected to provide insight into spatial and UI metaphors.

Keywords: *spatial thinking, user interface, UI metaphors, spatial metaphors*

ملخص. تستكشف هذه الدراسة العلاقة بين تطور الأفكار المكانية واستخدام واجهة المستخدم في الأدوات الرقمية الداعمة لها، بهدف متابعة التنقل العقلي والرقمي في عملية التصميم. تم تقييم الاستعارات المكانية في محور هذا الاستكشاف من خلال وظائف الواجهة المكانية، والتي توفر للمصممين القدرة على التعامل مع الأشياء وبيئاتها في بيئة ثلاثية الأبعاد. في دراسة الحالة التجريبية التي أجريت مع 4 مصممين، تم استخدام سيناريوهين مختلفين باستخدام نفس المواد. وتمت مقارنة الأساليب المختلفة للتعبير البصري للاستعارات المكانية على هذين السيناريوهين. في السيناريو الأول مع مشاركين اثنين، يقوم المشاركون بتنفيذ المهام من خلال الرسومات التخطيطية والرسوم البيانية. وفي السيناريو الآخر، يقوم المشاركون بإكمال نفس المهام أثناء عملية النمذجة ثلاثية الأبعاد. ومن المتوقع أن توفر هذه المخرجات، التي تعد مظهرًا مرئيًا للتفكير المكاني للمصمم، نظرة ثاقبة للاستعارات المكانية واستعارات واجهة المستخدم.

VISUAL APPROACHES ON SPATIAL THINKING: USER INTERFACE METAPHORS

الكلمات المفتاحية: التفكير المكاني، واجهة المستخدم، استعارات واجهة المستخدم، الاستعارات الفراغية.

1. Introduction

Spatial thinking is the ability to think and reason about information in terms of its spatial relationships. Therefore, the nature of space can be thought of as a process where spatial information representation and spatial reasoning are integrated (Lee & Bednarz, 2005). Spatial thinking, which includes mental processes related to representation and spatial relationship inferences, corresponds to relationships between objects or within objects (Uttal et al., 2013). The representations implied here consist of elements and spatial or conceptual relationships between elements with respect to a frame of reference (NRC, 2006).

In the design process, both metaphors and representations have an important role for the designer's spatial thinking, establishing relationships in space and designing according to this space. Physical or digital toolkits that allow the designer to represent the design idea are also part of spatial thinking. Therefore, depending on the toolkit used, the spatial thinking process of the designer and the metaphors used in this process will also vary. From pen and paper to the toolkits of digital design programs, the design environment provides a space for the designer to represent their ideas. But unlike a pencil-and-paper design, user interfaces provide a simulation environment for external representations of spatial thinking (Card et al., 1999) and create controls for the virtual space with interface components suitable for their functions. 3D modeling platforms in the design process provide a digital representation of the design idea by allowing users to edit and manipulate the object-environment relationship. In the context of spatial thinking, the projection of the designer's relationship with metaphor is discussed through metaphor - design process and metaphor - user interface within the scope of this study.

The aim of this study is to gain an understanding of encoding the spatial thinking process in the design process through user interface metaphors. The designer makes use of various 2D and 3D representation methods in the design process. A pilot case study was conducted to evaluate the metaphors followed through these representations in the context of spatial thinking. The metaphors used by the participants who produced 2D output with digital sketches and diagrams and the participants who performed the same tasks by modeling in the digital environment were interpreted by matching them with the actions they performed on the interface. The case study, which allows the spatial thinking and design process relationship to be evaluated in the context of user interface metaphors, also paved the way for the evaluation of metaphors through intent and inference.

2. Spatial Thinking in the Design Process

The design process is based on skills such as poorly defined problem solving, productive approach, spatial thinking and modeling (Cross, 1995). In this process, the designers express their mental representations by producing external representations, in this sense, the design process is also a cognitive activity (Kim and Maher, 2008). Spatial thinking skill, which is one of the important key points of this cognitive process, is based on the ability of designers to perform various translation operations by understanding the spatial positions of objects and their relationships with each other (Sutton and Williams, 2007). It is a spatial ability to make inferences about 3D objects from 2D images (Sutton et al, 2005) and to interpret the attributes of objects such as location, size and position through inferences in terms of their relations with each other. In this context, there are processes in the mental manipulation of a design idea in 2D or 3D: creation of a visual image, changes due to its location and spatial structure in the space, changes in the space itself (Danchenko, 2021).

The spatial thinking ability, which enables to make more basic inferences by analyzing complex object and environment relations, makes it possible to construct new levels of difficulty based on these basic inferences. In the process of transferring mental representations to external representations in the design process, these new spatial constructs directly affect the solution of the design problem. The designer, who interacts with the environment mentally or physically, transfers the spatial thinking ability to the design with physical tools such as paper-pen or mouse-keyboard-screen during the design process. Using spatial thinking, designers can grasp how the various components of a design interact with each other in the real world. Understanding how various design components will appear from different perspectives and how they will interact with other elements in the design space will help create spatial relationships. Designers direct their design in terms of both object and space based as well as physical and digital environment based during the design process. They can benefit from spatial thinking and metaphors as problem-solving tools by externalizing the representations in their minds.

3. Spatial Thinking Through Metaphors

Spatial thinking is based on mental representations associated with the space-based attributes of the physical world and on the interaction with these representations. The connections between the real-world entities and the mental world entities are mapped by representations. Humans use mental images to make sense of abstract ideas that are challenging to communicate verbally. The goal of both representation and metaphor is to convey the invisible by making it more visible in various ways. Instead of reflecting an objective and literal mode of representation, metaphors have a dynamic, context-based structure (Hogan, 2008).

In the design process, both metaphors and representations have an important role for the designer's spatial thinking, establishing relationships in space and designing according to this space. The metaphorical dialogue continues both in the designer's mind and in the interaction with the user interface by supporting the spatial thinking. Physical or digital toolkits that allow the designer to represent the design idea are also part of spatial thinking. Therefore, depending on the toolkit used, the spatial thinking process of the designer and the metaphors used in this process will also vary. From pen and paper to the toolkits of digital design programs, the design environment provides a space for the designer to represent their ideas. But unlike a pencil-and-paper design, user interfaces provide a simulation environment for external representations of spatial thinking (Card et al., 1999) and create controls for the virtual space with interface components suitable for their functions. 3D modeling platforms in the design process provide a digital representation of the design idea by allowing users to edit and manipulate the object-environment relationship. In the context of spatial thinking, the projection of the designer's relationship with metaphor is discussed through metaphor - design process and metaphor - user interface within the scope of this study.

3.1. METAPHORS IN THE DESIGN PROCESS

Considered in the context of the design process, a parallelism can be established between the processes of representing the design idea and the processes of metaphorical representation. In terms of representing information, designers can benefit from metaphors as a tool for organization and as a mental guide (Hogan, 2008). An abstract idea of an intellectually conceived design may have a vague representation in the space of the designer's mind. However, when it comes to the interpersonal level, this idea will need to be described through a verbal or verbal filter in order to embody it. Textual or verbal use of words, which constitute the way of interpersonal communication, will create a new channel for transferring the metaphor to the other party. The visual equivalent of metaphors will establish an intellectual bridge between people. This bridge, which is provided by metaphor, will find a response in the physical world with the representation tools chosen by the designer. Representations used in the context of different models and environments, present a space surrounded by metaphors in the interfaces between mental, physical, and digital. The understanding provided by 2D and 3D representations goes one step further with digital tools allowing interfaces to offer movement and perception capability within a representative space.

Metaphors, which are a toolkit used by the designer in the design process (Cila, 2013; Murray-Rust et al, 2022), help the process of understanding and gaining new meanings (Pee et al, 2015). Before the use and area of influence of digital tools in the design process expanded, sketches and physical models, which were described as traditional methods, were the tool sets in which the designer made decisions through bodily interaction. Metaphors, which are effective in the designer's view of the design problem as a metaphor, reach the problem research as a source and design as a target (Hey and Agogino, 2007). In the design activity carried out through a digital design tool, UI metaphors are included in this process as well as metaphors for the design problem. The metaphor creates a buffer zone both in the embodiment of the design idea and in the interpretation of the interface of the design tool. The subject is the designer interacting with both the design tool and the design idea. The see - move - see approach here turns into a two-pronged feedback space and provides a recursive domain between both the problem and the designer and the designer and the design tool.

3.2. METAPHORS IN USER INTERFACES

User interfaces, which include the tools and representations used in a design process, also enable functions such as creating, interacting, changing, and sharing these representations (Resnick et al., 2005). User interfaces, which is one of the main topics in the human - computer interaction (HCI) framework, often makes use of metaphors depending on the traditional function-oriented approach of HCI. The use of metaphor, which is based on the use of users' experiences in different fields to increase the intelligibility of a system, aims to represent concepts and images that are already in the minds of computer users, thus reducing the mental workload of users.

Fineman (2004), who interprets the interface and metaphor relationship through direct manipulation, navigation, and human interaction, groups the basic metaphorical approaches used in HCI under these headings. Tools such as *pencils*, *erasers* and *rulers* in the interface of a design platform in the digital environment are equipment that the designer also uses in the physical world. Using these tools, the designer can *draw, delete, measure between two lines* on the screen, and continue to use their current knowledge while performing this direct manipulation. Navigation metaphors are metaphors that enable the designer to explore a digital product and its environment in the context of the design process. It is also possible with digital navigation tools to explore a place in the physical world by *walking around* and *looking at it from different angles*. In this sense, the digital world benefits from the metaphors of the physical environment such as *going back and forth*, *searching* and *navigating*. Human interaction basically refers to the interaction between people in the physical world. Interactions such as a digital tool offering alternative suggestions to the user, providing *help menus*, *getting approval* with dialog boxes are small but essential steps in the dialogue that interface systems establish with humans. In this way, the user can establish a more natural interaction with the interface by following the communication ways they are already familiar with (Norman, 2010).

Design ideas transferred from the mind of the designer to the digital environment through the UI can be supported by spatial functions within the UI. Designers can use spatial layout to organize the geometric forms or conceptual relationships; this can include grouping related components together, using whitespace to separate different sections of the interface, and using visual cues. The sense of spatial navigation allows users to move through and interact with the interface in the design process. Functions such as *scrolling, panning,* and *zooming* can be used by designers to explore the interface. Also, designers can use spatial metaphors to both represent their design ideas and interact with the UI. Concepts such as *connection, speed, portal, door,* and *navigation,* which are the most used metaphors in accessing the virtual world, are spatial metaphors (NRC, 2006). The spatial nature of even the metaphors that form the backbone of online access to the virtual world is an indication that the flow of information is also spatial.

4. Pilot Study

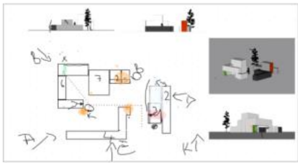
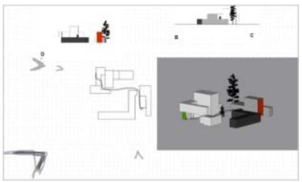
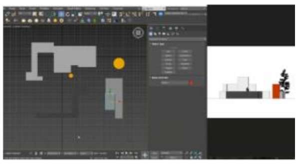
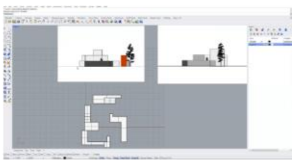
A case study was conducted with 4 participants to understand the embodiment of spatial metaphors used in the design process, In order to ensure continuity in the processes of the participants, time constraints were not applied in the tasks and the design was not interrupted. After the tasks that lasted approximately 30 - 50 minutes, interviews were conducted with the participants over semi-structured questions. All participants are architects. One of the participants performing each scenario regularly uses the technique mentioned in the scenario during the design process (A1 and B1). Other participants in the scenarios stated that they did not use it actively or for a while (A2 and B2). All participants were given 4 different images of the same model. Two of these images are axonometric views and two are side views. In the model, there are 3 interrelated main masses, and two tree figures and a human figure have been added to refer to the real-world space and strengthen the relationship between the masses. Participants were encouraged to think aloud throughout the process.

• Scenario A: 2 participants explained the spatial relationships between these images in the digital environment using sketches and diagrams.

• Scenario B: The other two participants interpreted the spatial relationships of the same images by creating a 3D model.

Table 1 shows the general information about the participants and the visual outputs on which the participants evaluated the results during the pilot study.

TABLE 1. Pilot Study overview (F: female, M: male).

Part.	Scenario and technique	Tool	Frequency of using the technique	Duration	Visual Output
A1 (F)	A - sketches and diagrams	Zoom - Whiteboard	Actively using	32 min	
A2 (F)	A - sketches and diagrams	Zoom - Whiteboard	Not actively usign	40 min	
B1 (F)	B - 3D modelling	3DsMax	Actively using	27 min	
B2 (M)	B - 3D modelling	Rhino	Not actively usign	48 min	

Within the scope of the test, the following 3 tasks were requested from the participants:

- Task 1. Scenario A - Can you describe what you saw and the connections between them on a plan as a sketch/diagram? Scenario B - Can you describe what you saw and the connections between them by creating a 3D model?
- Task 2. Can you mark the positions of the 4 images on the visual output?
- Task 3. How would you describe the route that will take you from the green point marked in the images to the orange point?

According to the possible results of the case study, it is aimed to provide an insight to evaluate the use of metaphors in the context of spatial thinking and design relationship from the user interface perspective.

4.1. EVALUATING METAPHORS AND SPATIAL INTENTIONS

The representation of the masses and relations between the masses, which are desired to be created by sketching and modeling according to the reference images given, is based on the process of spatial thinking and making spatial inferences. Participants used metaphors frequently throughout the process and conveyed spatial relationships through these metaphors. The fact that the masses in the reference images can be correlated in terms of location and size has paved the way for the use of spatial metaphors in the interpretations made through sketches and models.

The participants completed the tasks by following different steps and using different expressions according to the tool they used and their own spatial perception. In line with the aim of the pilot study, two different approaches were evaluated to determine possible textures for the spatial metaphors used in the design process. According to the metaphorical explanations used, primarily spatial metaphors in the transcripts are labeled. A transcript analysis was conducted for the metaphorical expressions used by each participant during the interviews with the participants and the actions they took in the process of saying these expressions. Using the classification for metaphors in interfaces (Fineman, 2004), each spatial metaphorical expression was labeled as *direct manipulation* and *navigation*. No expression to be labeled as *human interaction* was encountered in the existing transcripts. *Semantic* tag was used for semantic metaphors that may arise from the design scenarios given in the study or the metaphorical discourses that the person's language is familiar with.

In this labeling made with reference to Fineman's categorization in the context of metaphor and HCI relationship, metaphorical explanations are interpreted as *spatial intentions* (Table 2). In the design process, an expression of thought or an action is carried out in line with certain purposes, namely intentions. These intentions are the result of an effort to associate objects and space in the digital environment. The participants represented the objects they saw from the images through different components by passing them through their own spatial thinking filters. Direct manipulation is possible in objects that are spatially associated and involved in the design process, based on the metaphor of REPRESENTATION COMPONENT IS A PHYSICAL OBJECT. The metaphor of REPRESENTATION COMPONENT IS IN PHYSICAL SPACE emphasizes that the components represented in the digital environment are in a physical environment.

TABLE 2. Metaphorical expressions according to spatial intentions in the context of metaphor and HCI relationship.

Participant	Metaphoric Expressions	Spatial Intention
A1	... let me try to *put* this	Direct Manipulation
	... *set* them now	
A2	... *enlarge* this component a little	
	... *move* it when it's in the space	
B1	... couldn't *get* the section	
B2	... *create* an element from here again	
	... *removed* that element	
A1	... if we *look from above*, it's like this	Navigation
	... for *going clockwise*	
	... *positioning* of 7 a bit wrong	
	... that mass is straight when we look from the side	
A2	... so I can see *a space next to that* red	
	... select all and *scroll up*	
	... see it's *more than half passing*	
	... the figure *continues below*	
	... side by side *based on perspective*	
B1	... the thing *in the back* is the piece	
	... the others must *be seen through*	
	... just *looking from the inside*, at human height	
	... surroundings look different when *zooms in and out*	
B2	... look at the first element *from the top*, this is	
	... this view, this *rear view*	
	... don't have a *view from above*	
	... the outer line if perceive *from the side*	
A1	... can't *encode* that little mass over there	Semantic
	... *highlight* with text	
	... part 6 *stuck in my head*	
A2	... *set my eyes* on it	
	... next in line is *like an L*	
B1	... this *goes L* shaped	
B2	... go *based on clear numbers*	
	... won't be able to *put forward*	
	... roughly *figure this out*	
	... *reveal* a consistent thing	

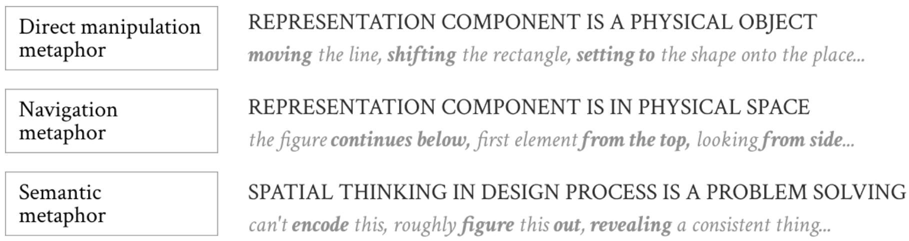


Figure 1. HCI metaphors according to the result of the case study.

The participants, who used expressions such as an object is *behind*, the line *continues in the downward direction*, *being aligned* from the *top view*, expressed all the representation forms in the digital environment by making use of physical space descriptions. As the expectation from the participants within the scope of the given tasks is to create representations of the visuals in the images in different environments, the participants also treated the spatial relations as a problem-solving process to create these design representations. Expressions such as encoding the mass, solving the objects also point to this. In addition, the participants also used expressions such as like *L-shape*, like an *entering* or *square*, similar to *S form* while expressing the parts they had difficulty in deciphering.

4.2. EVALUATING METAPHORS AND SPATIAL INFERENCES

Table 3 shows these spatial inferences and exemplary metaphorical expressions. The expression-representation relationship of the participants makes it possible to make metaphor-based spatial inferences, and the spatial inferences made in this context are discussed under three headings.

1. Interaction-based descriptions: It covers the tool-based actions during the interaction of the participants with the interface. There are use cases for different platforms, as all four of the participants perform tasks in digital programs. However, the spatial relationship-oriented nature of the tasks pushed the participants to a more problem-solving approach, and metaphorical expressions of interaction with the interface were encountered less frequently.

2. Object-based comparisons: The spatial relationship of objects is based on comparison with each other. Each participant, while making use of direct manipulation and navigation metaphors, defines the relationship of objects by making a spatial comparison.

3. Situation-based interpretations: These metaphors, which are used by the participants to better understand and explain the current situation, also include semantic metaphors. While establishing spatial relations, they include interpretations such as simulating forms, describing situations, and naming objects.

TABLE 3. Metaphorical expressions according to spatial inferences according to expression-representation relationship.

Participant	Metaphoric Expressions	Spatial Inference
A1	... let me *get away* from here	interaction-based descriptions
A2	... first *called* the rectangle	
	... *draw* with line but *make straight* with shift	
B1	... when *shrink,* the icons over there are *gone*	
B2	... *proceed from* the top view	
	... *come to* perspective, *extrude* 5 units	
A1	... but this point, for example, is *a bit passing* this one	object-based comparisons
	... there's *something connected,* but *at a lower level*	
	... this one is *higher,* that one is *lower, lower,* and *longer than* this	
	... can't see if *the one below* and *the one at the back* are the same	
A2	... it *comes to an end* here, but it *continues a bit further by extending* from here	
	... here, it looks *a bit behind, a bit further back*, and appears *thicker*	
	... it was *ending in front of* the dark gray, it was *ahead*	
B1	... it is *a bit ahead, l*ike a box, it *goes like* this	
	... it looks *perfectly equal,* but is this part *longer*?	
	... it's like the end of this one is *holding the end of* that one	
	... they *split into two,* one *rises*, the other *continues*	
	... see this, this *doesn't go all the way then*	
B2	... we also see this *from the opposite side,* this one is *overtaking it*	
	... because this point and these two *don't match*	
	... it *comes out from the side* and *goes quite far in that direction*	
	... checked if it *goes through,* but no, it is *quite cut off from behind*	
A1	... there is *a slight gap between* them	situation-based interpretations
	... these parts are *just a click away*	
	... sounds like *an entering* or *an inviting part*	
A2	... like it didn't *pick up* where I *left off,* it's like there's *a space left*	
	... here is *returning an L* like this	
B1	... there is *a ledge*	
	... let's say we *sat it down*	
B2	... now it will be *driven a wedge between*	
	... will *subtract the data* from the plan	
	... 5 seems to *come from within* that	

In the semi-structured interviews held after the tasks, the participants evaluated their own processes. A1 mentioned that it took time to place the forms in her mind at first and stated that the axonometric-I visual greatly influenced her perspective. She stated that she positioned herself directly according to that perspective, as she presented the view from the *highest level*. While positioning the visuals within the scope of the second task, participant A1 preferred to draw the main directions on the plan she had drawn and explained the images in the direction she assigned, using the expressions *north, south, east*, and *west*. In the third task, while describing the distance between two points, she created functional relations rather than the forms and spatial relations of the masses. She used expressions such as *through the square, turn right from the tree in that square* and interpreted the space between the masses as a *square*.

When A2 compared the images and her plan after completing the drawing, she realized that the narrow space she perceived in the axonometric images was quite wide. Stating that she was surprised that it was different from what she first perceived, A2 stated that she had thought of most masses differently before drawing, but these perspectives changed one by one as she continued to draw the relations between the masses. Although she positioned the other images correctly in the second task, she initially marked the axonometric-I image in the wrong place. Then, realizing her mistake, she said, 'Assuming that I have installed a camera, for some reason I thought about the plan by turning it around'. A2, like A1, used the semantic metaphorical discourse based on function by saying *courtyard* while expressing the space between the masses.

The first participant B1, who performed the modeling tasks, proceeded by modeling what she saw in the images directly while constructing the spatial relationships and frequently gained control of the images by changing their perspectives in the model. For this reason, the metaphors used by B1 are generally navigation-based and completed the model by comparing the relationships between objects in space. While creating the model, B1, who completed the second task very quickly thanks to the controls she made from the images, used expressions such as *looking from the right* and *looking at the bottom left*. This situation supports the participant's interpretation of the images according to the reference frame she created on the axis of her own model. In the third task, while describing between two points, she descended directly to the *level of the human eye* in the modeling environment and examined the masses from a close perspective. Like the other two participants, she stated that she could describe the space as a *courtyard* or a *garden*.

Unlike the other three participants, participant B2 preferred to use images as a metric reference. He determined the reference coefficient for the masses in the images on the Rhino program he used and pasted the whole model in line with these coefficients. He was able to obtain a very accurate visual result in terms of size and location during the design process, which took longer than other participants. He discovered that the masses in the image were prepared with a modular system, and after a while during his modeling, he made measurements by using this modular approach. After drawing mostly on the plan, he proceeded by determining the lengths of the masses in the vertical direction. Therefore, its navigation in the modeling space is not as frequent as B1. In describing the distance between two points, the participant used the term *semi-open space* and underlined that this perception of gap increased after modeling.

4.3. CONSTRAINTS

As the pilot study was conducted in the native language of the participants and authors, the metaphor descriptions included in the research were then translated into English by the authors. Although metaphor studies are evaluated in a language-based framework, Lakoff and Johnson (1980) mention that metaphors provide action integrity and shape the flow of thought. In this sense, it is expected that the translations will provide a consistent result in terms of metaphor and action comparison. Although the test, which was carried out with 4 people in total, with two participants for both scenarios, provides efficient outputs in terms of metaphor representation, it will provide more comparable results if it is carried out with more participants in the future.

5. Discussion

The spatial metaphors that designers use in the face of a design problem that triggers spatial thinking processes may vary depending on the design tool interface used in the process. However, even if the metaphorical expressions used change, it is possible to evaluate the projections of the actions performed by the designers on the interface in this process within the scope of spatial intention and spatial inference. Designers explore space by positioning their observer's point of view with reference to the interface they use. The reinterpretation of the relation between the object and the environment associated with space in the context of the interface allows the designer to transfer the spatial metaphors used in the physical world to the virtual world. While constructing an object and inter-object relations, information in the physical world is referenced, so designers move objects, move between objects and try to solve spatial relationships.

This study explores the metaphors that support spatial thinking in the interfaces of existing digital design tools by evaluating the expressions and actions of the designers in this process through a case study. Presenting an understanding effort for spatial thinking in the design process based on personal experiences, subjective interpretations, and preferences, this study provides a framework for new user interface metaphors that support the spatial thinking process in the future.

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AR + DESIGN

An experiment in remote teaching and practice using augmented reality for interactive brick-based structure design

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Abstract. Due to the *COVID-19* breakout and its epidemic prevention restrictions, remote communication has become one of the critical solutions that almost every industry is exploring in this post-epidemic era. Likewise, architectural practitioners also look at remote possibilities for current design methods. This paper presents a unique experimental research using augmented reality (AR) immersion technology for interactive brick-based structure design to explore a remote design method overlayed on the spatial context in the architectural draft visualisation and modification stages. It discusses the teaching process and practice outcomes from an online workshop, which is conceptualised to allow participants to learn, master, and apply the proposed remote design method in AR for brick-based structures. For this online workshop, we enrich the current parametric design method to an AR-assisted way for remote possibilities. The employed workflow was driven by an instant connection between 3D modelling software (*Rhinoceros 3D*), the parametric design plugin (*Grasshopper*), and the AR immersion plugin (*Fologram*). This experiment explored and validated the possibility of remote teaching and practice in architectural design education for post-epidemic era requirements.

Keywords: *Augmented Reality (AR), Remote Design, Brick-based Structure, Online Teaching and Practice.*

ملخص. نظرًا لتفشي فيروس كورونا (COVID-19) وقيود الوقاية من الأوبئة، أصبح الاتصال عن بعد أحد الحلول الحاسمة التي تنتهجها كل صناعة تقريبًا في عصر ما بعد الوباء. وبالمثل، ينظر ممارسو المهنة من المعماريين أيضًا إلى كافة الاحتمالات الحالية لطرق التصميم عن بعد. تقدم هذه الورقة بحثًا تجريبيًا فريدًا باستخدام تقنية الغمر بالواقع المعزز (AR) لتصميم المنشآت التفاعلية القائمة على البناء بالطوب لاستكشاف طريقة تصميم عن بعد متراكبة على السياق المكاني في مراحل تصور المسودة المعمارية وتعديلها.

ويناقش البحث عملية التدريس ونتائج الممارسة من خلال ورشة عمل عبر الإنترنت، والتي تم تصميمها للسماح للمشاركين بالتعلم وإتقان وتطبيق الطريقة المقترحة للتصميم عن بعد في الواقع المعزز للمنشآت القائمة على البناء بالطوب. ونقوم فى تلك الورشة بإثراء طريقة التصميم البارامترية الحالية بطريقة مدعومة بالواقع المعزز لإمكانات التصميم عن بعد. وقد تم تصميم سير العمل ليكون مدفوعًا بالاتصال الفوري بين برنامج النمذجة ثلاثية الأبعاد (Rhinoceros 3D)، والبرنامج المساعد للتصميم البارامترى (Grasshopper)، والبرنامج المساعد للغمر في الواقع المعزز (Fologram). وقد استكشفت هذه التجربة وتحققت من إمكانية التدريس والممارسة عن بعد في تعليم التصميم المعماري لمتطلبات عصر ما بعد الوباء.

الكلمات المفتاحية: *الواقع المعزز، التصميم عن بعد، المنشآت القائمة على البناء بالطوب، التعليم والممارسة المهنية عبر الانترنت.*

1. Introduction

Under the influence of the *COVID-19* pandemic, most architectural teachings have been moved online. Due to the sudden shift from in-person communication on campus to virtual alternatives, both instructors and students are experiencing dramatic changes in their current modes of teaching and practice (Duaa et al., 2021). Prior to this, they did not have enough related experience in remote education for reference. Moreover, the conventional sketch or screen-based design approaches lack actual scale and spatial awareness, which means that designers can not predict the draft within the related context, so that the outcome may deviate from the design idea. The research gap exists that the conventional design methods are suitable for students who have essential specific architectural knowledge and skills with the help of in-person teaching, but not ideal for the beginner without a sense of scale, especially under the conditions of remote communication. Therefore, the above changes and challenges have inspired many researchers to explore and develop augmented architectural teaching and practice modes for the current pandemic remote needs (Antonio and Lucas, 2021).

Recently, with the rapid development of immersive technologies, AR, which has the unique feature of combining virtual models and real-world context, has gradually entered the field of vision of architectural practitioners (Song et al., 2021). Related AR devices have significantly developed and are widely available in architectural construction fields these days (Wang et al., 2016). Besides its application on construction sites, AR technology also brings possibilities for the architectural design process through features such as registering and aligning the physical environment with virtual objects, and running interactively in real-time (Krevelen and Poelman, 2010). Greg Lynn is one of the first architects to use AR technology in the architectural design stage, but focusing only on contextual design drafts with the holographic visualisation preview method (Frearson, 2016). By being able to understand 3D models in an immersive environment, architecture students could be much more effective in their perception and memorising the design drafts (Christopher et al., 2020). However, the interactivity of AR technology should not be overlooked in the design stage. The AR interactions seem to have the possibility for interventing design data and results. Especially in remote situations, interactive experience with immersive visualisation is considered to potentially provide a new mode of architectural design education in the post-epidemic era (Immanuel, 2013). Moreover, with the popularity of AR apps for mobile phones and related development software, there is a chance to promote this immersive experience to users from anywhere (Abboud, 2014). Therefore, utilising AR immersion technology for remote architectural design education can be witnessed.

This paper presents an experiment in remote teaching and practice using AR for interactive brick-based structure design, delivered online during the pandemic. It instructed as a case study to gain a deeper understanding of the potential and limitations of new remote technology in architectural design education. This research starts with the AR design algorithm development, which allows participants from different locations to customise the design logic; followed by AR interactive input development, which enables users to preview and modify design drafts with spatial context; and validates the AR design method through brick-based structure design experiments during the online workshop. Additionally, this workshop is used as an example to reflect on online teaching and remote practice in architectural design education.

2. Methodology

The *AR + Design* online workshop was instructed by the author in November 2022. Due to the pandemic restrictions in different countries, this workshop had to be conducted remotely online, which brought the following challenges: a) the workshop format, we have to develop an architectural design method suitable for online teaching and remote practice so that participants can join from anywhere; b) the workshop design topic, we need to choose an architectural material and structural form, which meet the design algorithm and remote requirements for individual work; c) the remote teaching and practice interface, we propose to enrich the current design method with applying AR as the interface for participants to fully immersed in learning and design experience; d) the workshop tools, we have to ensure the related software and devices are ubiquitous so that all the participants can access and manipulate the task by themselves.

Reacting to the above challenges, the workshop instructor built a remote architectural design method for the online teaching format using mobile AR as the remote and immersion interface. This design method for remote teaching and practice was verified with the brick-based structure design through AR. The reason for choosing brick as the material is that it is one of the most widely used building materials, and brick-based structure design logic follows parametric rules, making it easy for students to understand and develop in a parametric way. This workshop also transformed the conventional design method to the plugin-oriented AR immersive way in the current architectural modelling software environment, which is familiar for architectural practitioners to understand and develop. The employed method was driven by an instant connection between *Rhinoceros 3D*, *Grasshopper*, and *Fologram* from participants' laptops. At the same time, implementing the *Fologram App* (the *Fologram* mobile device client), which synchronised the digital design and data from *Rhinoceros 3D* and *Grasshopper* on their laptops to the AR environment, enables the participants to achieve the AR design with their smartphones from their locations.

The workshop task for the participants was to use AR technology to design a customised brick-based structure immersively for their own space or surrounding environment. This design draft was proposed to generate and modify through AR interactions with parametric design rules and visualise through AR with spatial contexts in real-time at a 1:1 ratio to increase the perception of space and scale.

This online workshop was taken by 49 participants, consisting of 37 bachelor students majoring in architecture and interior design (more than half of them were in the first year), nine master students majoring in architecture design, and three graduates (two interior designers and one assistant professor). They all know 3D modelling software, but only 14 students had parametric design experience with *Grasshopper*. The AR immersion experience and mobile AR were new to all participants, but only two students had previously worked with AR-related projects.

The workshop was limited to two days. Before the workshop, the participants were asked to install and test the essential plugins and related devices to make the most of the available time. The workshop schedule was split between introduction lectures, a parametric design algorithm tutorial, an AR plugin tutorial, an AR design demonstration, a remote AR design experiment, and final reviews (Figure 1).

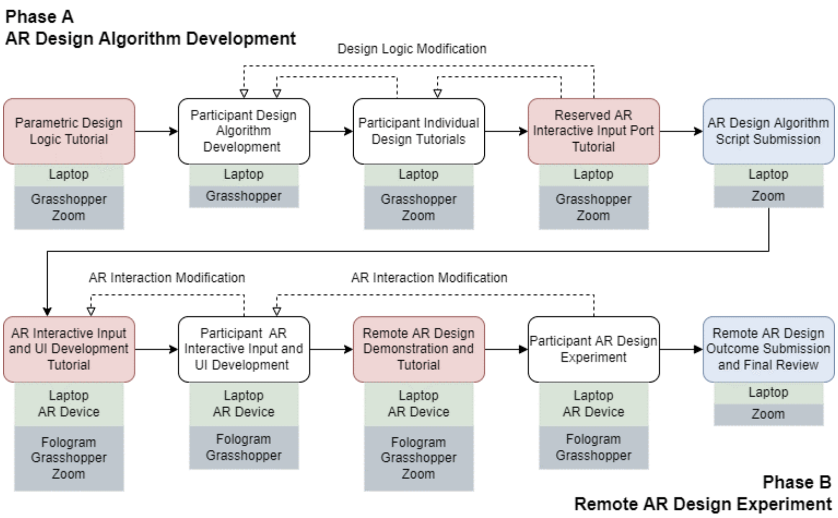

Figure 1. This is the organised process of the *AR + Design* online workshop from Phase A - AR design algorithm development (above) to Phase B - remote AR design experiment (below). The tutorials from the workshop instructor are coloured in red, as well as the submission steps from participants are coloured in blue. The related devices and software for the online workshop and remote AR design experiment are coloured in green and grey.

On the first day, participants received introductory lectures about parametric design and AR technology in architectural fields. After that, the instructor delivered a tutorial for the parametric brick-based design algorithm, to demonstrate the logic of the parametric design and reserve AR interaction inputs. These example files are based on the *Rhinoceros 3D* and *Grasshopper* modelling environment, which is easy for architectural participants to understand and modify. Participants need to develop their parametric design algorithms for brick-based structures after the first-day tutorial (Phase A).

On the second day, the author delivered Fologram tutorials to the participants on their mobile devices to demonstrate the essential interactive AR functions, including interactive input methods, holographic preview, QR code recognition, and AR UI developments. After that, participants have to plug the above AR interactions into developed design algorithms, choose a surrounding space, and design the structures remotely through AR (Phase B). The AR interactions and design outcomes have to be presented as videos or photos in the final review session at the end of this workshop.

3. Experiments and Findings

3.1. PHASE A: AR DESIGN ALGORITHM DEVELOPMENT

Phase A proposes an AR design algorithm based on parametric design logic with the possibility of accessing AR interactions. Compared with the conventional *Grasshopper* scripts, users are expected to reserve AR interactive input parameters in this design algorithm. The design topic is proposed to be an interactive parametric brick-based structure design, which is considered a suitable design form with straightforward parametric logic for the individual task. To achieve Phase A experiment, the participant needs a laptop with *Rhinoceros 3D*, *Grasshopper*, and *Fologram* installed.

To start with the AR design algorithm development, first, the workshop instructor gave a tutorial about basic parametric design logic. As an example for demonstration, the workshop instructor developed a brick column step by step in *Grasshopper*, and explained the parametric design process, including setting the column centre point, column radius and height, column rotation, brick pattern, layer rotation, etc., as editable parameters. Second, the workshop instructor introduced how to reserve and set interactive parameters for AR inputs in the existing developed parameter design algorithm. The AR interactive functions from *Fologram* and the corresponding response parameters from *Grasshopper* are also introduced and demonstrated by the instructor (Figure. 2). Last, participants need to duplicate the instructor's design process and change some parameter settings or imitate the instructor's design logic to develop customised algorithms, and reserve the parametric input ports for AR interactions in Phase B.

As for the outcomes, most participants chose to develop the AR design algorithm based on the instructor's script with different parameter input settings. However, only 14 students with advanced parametric design experience, developed their AR design algorithms in different logics. All the participants understand the logic of the parametric design and are able to set or modify specific parameters individually. In addition, participants mastered where and how to reserve AR interactive inputs to the existing design algorithm, including adjusting the structure height and radius, structure rotation, brick pattern, layer rotation, etc. (Figure. 3). Participants were asked to document their AR design algorithms in Phase B.

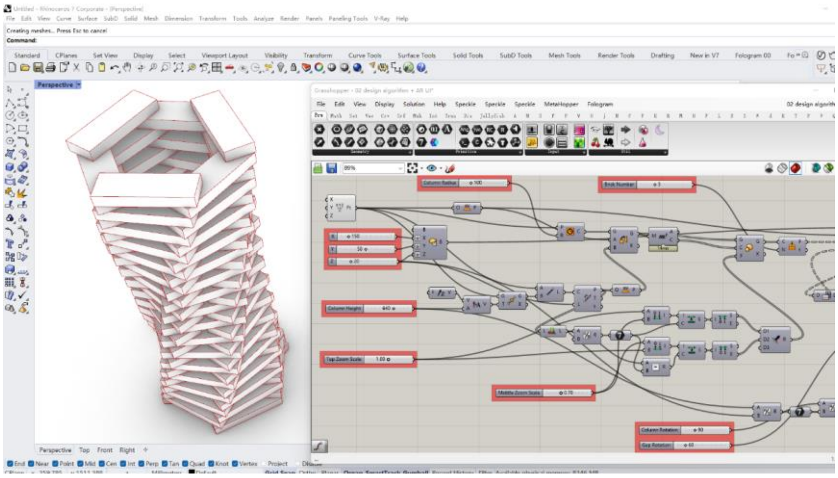

Figure 2. This is the parametric AR design algorithm for brick-based structures (a column as an example) from the workshop instructor's online demonstration, with the reserved AR interactive parameter input ports in the design algorithm script (coloured in red).

The findings of Phase A suggest that brick-based structures are suitable for beginners to understand and follow the parametric design logic, which has the simplest stacking form and design language. Such well-shaped regular elements make it easy for beginners to concentrate on the process of learning parametric design. Participants rated the brick-based structure favourably, and almost all the participants could finish the parametric design task, which means this design topic and structural scale are appropriate for the individual task. Moreover, since the AR interactive plugin is developed based on *Grasshopper*, the parametric design also meets the requirements of AR interactive input and immersive preview for remote teaching and practice. Therefore, the parametric brick-based structure design suits the workshop format and design topic needs. In addition, compared with the conventional design methods, the enriched AR design algorithm, which has the potential of remote immersion, is considered more suitable for online teaching and practice under the constraints of the pandemic.

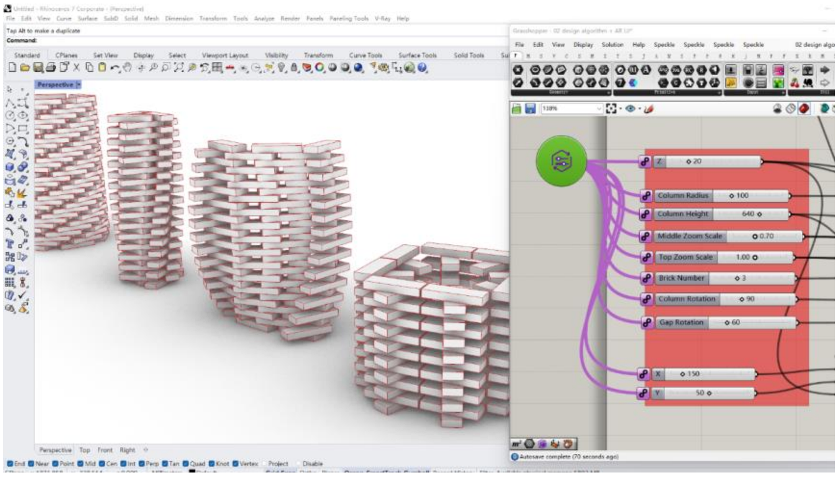

Figure 3. This is the parametric AR design algorithm for brick-based structures (columns and walls) in *Grasshopper* from some workshop participants' submissions in Phase A, with the reserved AR interactive parameter input ports in the design algorithm script (coloured in red).

3.2. PHASE B: REMOTE AR DESIGN EXPERIMENT

Phase B proposes a remote AR design experiment developed on parametric design logic and interacts with AR devices. Compared with the conventional sketch-ing or screen-based design method, users are expected to interfere with the design parameters through hand gestures on AR devices in this remote AR design experiment. The design results are proposed to align with the surrounding physical spaces and show as 1:1 holograms in AR to help users better understand and improve the design drafts. This remote AR design experiment aims to react to the needs and requirements for remote practice. To achieve Phase B experiment, the participant needs a laptop with *Rhinoceros 3D*, *Grasshopper*, and *Fologram* in-stalled, as well as a mobile device (smartphone or pad which supports *ARkit* or *ARcore*) with *Fologram App* installed.

To start with the remote AR design experiment, first, the workshop instructor delivered a tutorial with essential AR interactive functions from the Fologram plugin and introduced how to connect them with the reserved ports from the AR design algorithms developed in Phase A. As an example for demonstration, the workshop instructor showed AR interactive parameter inputs in *Fologram*, including AR number sliders, toggle, value list, buttons, track devices, sync objects, etc., for interactive inputs and holographic visualisation. Second, the instructor did live streaming demonstrations using the *Fologram App* user interface (UI) to achieve AR design with interactive inputs and on-site hologram preview through the mobile device screen-sharing (Figure. 4). Third, the instructor also demonstrated how to place the holographic design outcome with a QR code to the physical context in AR. Last, participants need to edit their AR ports in the design algorithms from Phase A with AR interactive parameters learned from Phase B. They can flexibly choose the interactive parameters which interfere with the structure radius and height, structure rotation, brick pattern, layer rotation, etc. After the algorithm modifications, participants would link the mobile AR device to the laptop to activate the remote AR design experiment. They could modify the interactive parameters immersively by hand gestures and preview the design outcome as holograms on-site in real-time through AR devices.

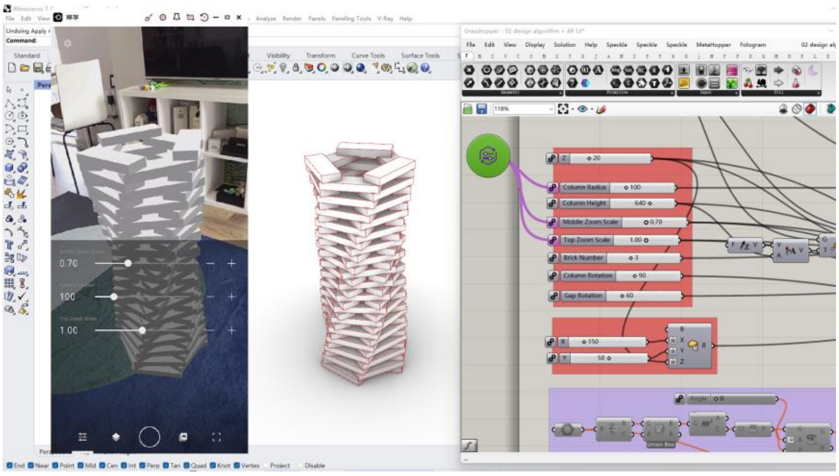

Figure 4. This is the online demonstration of using the *Fologram App* for remote AR design in Phase B (on the left). The *Fologram App* supports the holographic design draft on-site preview, and the UI interactive input (on the left), which corresponds and connects to the reserved AR interactive input ports in *Grasshopper* design algorithm scripts (on the right, *coloured in red*).

As for the outcomes, most participants designed brick-based structures successfully with AR interactions in their surrounding spaces through AR devices. They can master the AR input parameters with design algorithms and develop the *Fologram App* UI fluently. Moreover, 11 students with advanced parametric design knowledge, set the material synchronisation preview, which could add colour and texture to their holographic structure visualisation (Figure. 5). Participants were asked to document their final remote AR design algorithms as *Grasshopper* script files, record their remote AR design experiment as videos, and document the holographic outcomes as photos for the final review at the end of the workshop. During the final review, participants had extensive discussions with guest critics about their AR design outcomes and this remote practice experience (Figure 6).

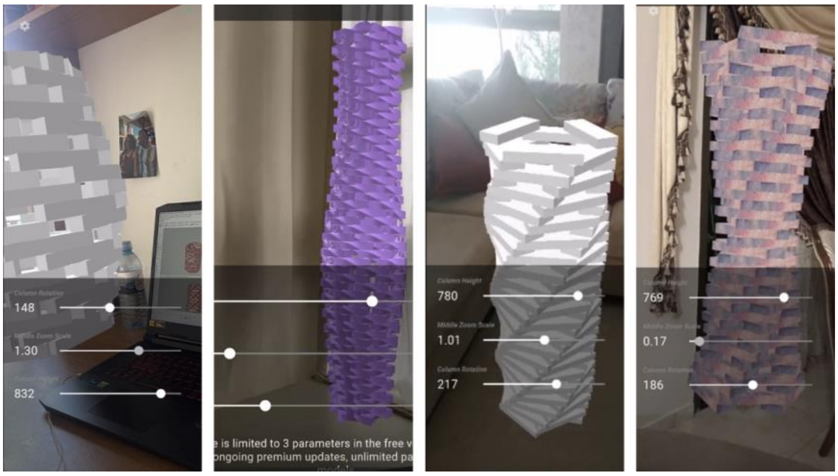

Figure 5. This is the screenshots from some participants' AR devices, demonstrating the AR interactive inputs from *Fologram App* UI and the process of remote AR design in real-time with on-site holographic preview in their surrounding spaces.

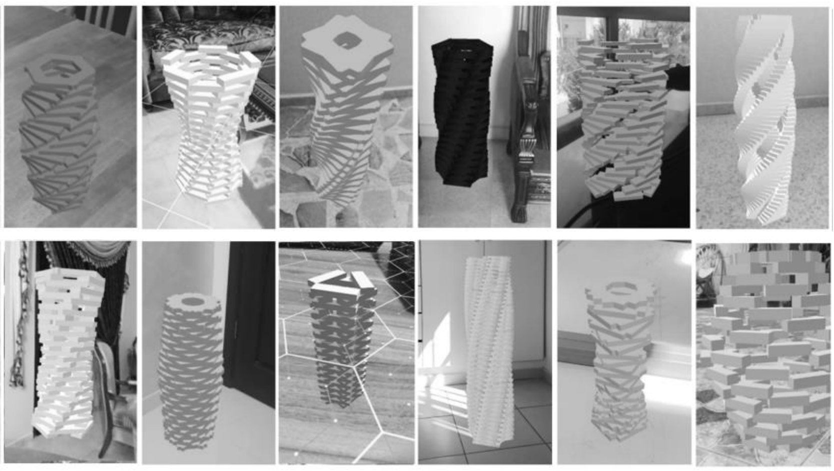

Figure 6. There are more remote AR design outcomes from different participants located in different spaces around the world in Phase B of the *AR + Design* online workshop.

Some participants did comparative experiments of the same design with and without AR-assisted collaborative versus, to find the similarities and differences in terms of spatial visualisation experience. The creation and development of design algorithms in *Grasshopper* are similar. However, without AR assistance, participants need to measure the surrounding environment on-site or model the surrounding environment into the design software to find the sense of the spatial scale of the design draft. Moreover, without AR-assisted collaborative versus, participants are only limited to screen-based preview and intuition to design the brick-based structures, which greatly reduces the creativity of the design and the comprehensiveness of space perception. At the same time, compared with the augmented way, the traditional design method takes more time to achieve the same design results, this is because it does not have an intuitive and immersive design draft preview, which can help designers improve design drafts more efficiently. Compared with the traditional design method, with the help of AR, participants can freely place the design drafts on-site for each location, and change the design in real-time according to the contextual environment. In the comparative experiment, the traditional design method cannot achieve this real-time on-site design and modification experience.

The findings of Phase B suggest that the AR design experiment is indeed different from conventional design methods. Users can design through direct hand gesture interactive inputs and preview the design outcomes as 3D holograms immersively to eliminate the shackles and defects of the 2D-based preview interface (2D documents or 2D-based screen visualisation). Participants believe the AR design method can increase their understanding of the design space scale, boot their design inspirations, and efficiently modify and preview design results, which they cannot experience in traditional design methods. Moreover, most participants felt that the required AR software and devices in this workshop were easier to learn and apply than standard modelling software. In addition, participants rated the remote AR design experiment favourably, and almost all the participants could finish the design and preview task from their own space and location, which means the design interface and tools are appropriate for remote teaching and practice under the constraints of the pandemic.

4. Conclusion

Associating the AR interactions with the parametric design algorithm will make it easier and more intuitive for architectural practitioners to create and adjust design proposals. The employment of AR provided holographic design outcome preview with actual spatial surroundings, as well as aided real-time evaluation and modification for design drafts. This AR design experiment fosters participants' creativity and spatial awareness in the initial architectural design steps, since updates and changes can be quickly previewed on-site. At the same time, using AR as an interface, allows remote participants to explore the 3D models from their own space and locations, which provides the possibility for remote teaching and practice.

Witnessing the participants' experiments, collecting their feedback, as well as analysing the *AR + Design* online workshop outcomes, it can be concluded that the participants' design experiences, including their spatial understandings and draft re-considerations, benefitted from the employed AR immersion technology. Due to the influence of *COVID-19*, the instructor aimed to use an alternative method utilising immersive experiments to visualise the design results in the physical space to compensate for the shortcomings of the current remote approach to architectural design education. Moreover, evaluating the participants' feedback, the workshop form and topic, tasks, design interface and tools used in this workshop are all suitable for remote participants to complete independently. This remote teaching and practice experiment showed that, the communication worked well through the online meeting software; the breakout rooms efficiently helped individual design tutorials; and the live streaming screen-sharing demonstrations of the AR design process helped participants understand tutorials pretty well remotely.

In conclusion, the *AR + Design* workshop presents unique experimental research using AR immersion technology for interactive brick-based structure design to explore and validate the possibility of remote teaching and practice mode in architectural design education for post-epidemic era requirements. Future investigations suggest promoting this remote experiment to head-mounted devices, since the current mobile AR device only provides screen-based immersive experiments, and participants crave a more direct, hands-free immersive experience. More design topics and structure forms need to be developed to validate this AR remote teaching and practice mode. Moreover, in the future, it is proposed to create a remote system that can transmit the instructor or critics virtually to the participants' surrounding spaces for an 'on-site' immersive preview and design guidance, which will significantly improve the remote experience of architectural education.

Acknowledgements

This experiment was validated by the ASCAAD 2022 online workshop, *AR+DESIGN: Augmented Reality immersive design method*, instructed by Yang Song. Fifty people participated in the workshop, including undergraduates, masters, PhDs, professors and other scholars with different architecture-related backgrounds. For the related workshop information, please check the ASCAAD 2022 workshop website (https://www.ascaad.org/conference/2022/workshops.htm).

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EMPLOYING EXTENDED REALITY (XR) TO EXPANDING NARRATIVES OF PLACE-MAKING, SPATIAL PRESENCE AND IMMERSIVE EXPERIENCE

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Abstract. Extended Reality XR, which encompasses various forms of virtual reality VR and augmented reality AR, has emerged as a powerful experimental tool in design and environmental psychology research due to its ability to produce comprehensive and immersive experiences for users through narratives. A strong sensation of spatial presence, which may be viewed as a subjective sense of space cognition and its surroundings, is one sign of a good XR experience. Despite the fact that XR research has shed light on numerous elements that may affect presence and place-making in XR environments, there is still much to learn about the varied phenomenology of narrative possibilities that ensure a successful immersion experience. The paper focuses on extended reality and how it influences how we create spaces, feel present in our surroundings, and have an immersive experience. In this paper, the concepts of place-making and spatial presence were examined in relation to how people might create a consistent sense of reality during both real-world and virtual experiences. The purpose of this study is to evaluate the ideas of place-making, presence, and immersion experience as they have been developed in XR research while also addressing variables that could affect expanding narratives. The study covers major elements of the "place" literature, connects them to the idea of presence, and then exhibits their use in the context of extended reality. It also discusses the phenomenological properties of presence in human consciousness. A user study conducted through a designed immersive experience as a simulation to some spaces of the Grand Egyptian Museum. Samples of users' responses were collected through a survey addressing their perceptions of the virtual visit. The study showed that place-making and spatial presence in extended reality work as a link between real-world locations and virtual attributes. When moving from the real world to the virtual one, boundaries become more fluid, themes can be developed, and virtual spaces mimic the real spaces. The study outline proposals for further work and lays out some ideas for future research.

Keywords: *Extended Reality, Space Narratives, Place-making, Spatial Presence, Immersive Experience.*

ملخص. برزت تقنية الواقع الممتد XR ، الذي يشتمل علي أشكالًا متعددة من تقنيات الواقع الافتراضي VR والواقع المعزز AR، كأداة تجريبية قوية في أبحاث التصميم وعلم النفس البيئي نظرًا لقدرته على إنتاج تجارب شاملة وغامرة للمستخدمين من خلال السرد. يدل الشعور الغامر بالوجود المكاني، والذي يعرف باعتباره شعورا ذاتيا للمستخدم يدرك فيه المكان والمناطق المحيطة به، علامة جيدة على التجربة المكانية في الواقع الممتد. وعلى الرغم من حقيقة أن أبحاث الواقع الممتد XR قد سلطت الضوء على العديد من العناصر التي قد تؤثر على الوجود وصنع المكان في البيئات الإفتراضية، لا يزال هناك الكثير لنتعلمه حول الظواهر المعقدة والمتنوعة للإمكانيات السردية التي تضمن تجربة انغماس ناجحة في المكان. تركز الورقة البحثية على الواقع الممتد وكيف يؤثر على كيفية إنشاء الحيزات، والشعور بالحضور في محيطها، والحصول على تجربة مكانية غامرة. تطرح هذه الورقة تساؤلات عن الإمكانات السردية لمفاهيم تختص بتقنية الواقع الممتدد والتجربة المكانية فيه. تم فحص مفاهيم صنع المكان والحضور المكاني فيما يتعلق بكيفية خلق شعورا بالحيز أثناء تجارب العالم الواقعي والافتراضي. وكان الغرض من هذه الدراسة هو تقييم أفكار صنع المكان، والحضور المكاني، وتجربة الانغماس وعرضها كما تم تطويرها في أبحاث XRالواقع الممتد مع معالجة المتغيرات التي يمكن أن تؤثر على توسيع نطاق السرد المكاني. اقترحت الدراسة خطابًا حول قيمة صناعة الأماكن وماذا يعني الشعور بالتواجد داخل بيئة افتراضية غامرة. تغطي هذه الدراسة العناصر الرئيسية لفكرة التواجد بالمكان، ثم تعرض استخدامها في سياق الواقع الممتد كما تناقش الخصائص لتواجد المكان في الوعي البشري. تم إجراء دراسة تطبيقية للواقع الممتد من خلال تجربة غامرة مصممة للمتحف المصري الكبير كنموذج وتم جمع عينات من ردود المستخدمين من خلال استبيان يتناول تصوراتهم للزيارة الافتراضية. أظهرت الدراسة أن صنع المكان والحضور المكاني في الواقع الممتد يعملان كحلقة وصل بين مواقع العالم الحقيقي والسمات الافتراضية. عند الانتقال من العالم الحقيقي إلى العالم الافتراضي، تصبح الحدود أكثر مرونة، ويمكن تطوير السمات حيث تحاكي المساحات الافتراضية المساحات الحقيقية. تحدد الدراسة مقترحات لمزيد من العمل وتضع بعض الأفكار للبحث في المستقبل.

الكلمات المفتاحية: *الواقع الممتد، السرديات المكانية ، صناعة المكان ، الحضور المكاني، التجربة الغامرة.*

1. Introduction

Our society is becoming more visually oriented (Nicholson-Cole, 2005), and decision-making processes now include information visualization (Sheppard et al., 2011). The term "sense of presence" has been used in virtual environment VE research to study the subjective experience of being in a specific location, even though it is physically located elsewhere, or to evaluate the degree of immersion (Lessiter et al., 2001). Virtual reality VR glasses are typically used to study sense of presence, however 2D screen approaches can also be used (Williams, 2014). The dominance of visual quality in immersiveness and presence has been contested by researchers. In light of this, it has been noted that sense of presence also includes spatial experience, such as the ability to move freely, soundscape, social interactions, and interactions with objects (Lindquist et al., 2016). The study proposes that there is a need for a viewpoint that opens up and addresses the capacity to convey the human connections to a place, that is, the perceived meanings and affordances of a place, in order to harness Extended Reality XR for communication in planning and to analyze their involvement in them. The idea that "places represent not only physical settings and activities within those settings, but also the meanings and emotions people associate with settings, influencing e.g. space planning and participation processes" (Davenport & Anderson, 2005) is the foundation of most scientific research in disciplines like geography, sociology, and psychology.

In light of this, we suggest that in order to help a wider audience grasp spatial data, a broadened and interdisciplinary understanding of the concept of immersion is necessary. The potential of emphasizing placemaking and narrative immersion in XR was examined in order to give users a deeper sense of presence and belonging.

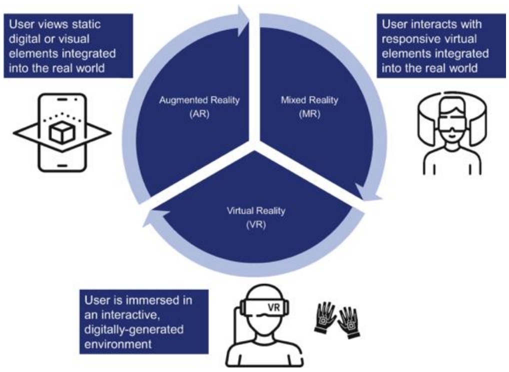

Figure 1. Extended Reality Technology and Applications of Augmented Reality, Mixed Reality and Virtual Reality. https://link.springer.com/chapter/10.1007/978-3-031-30089-9_3

2. Background

According to historical definitions of sense of place (Sebastien, 2020), these concepts encompass ideas of socially built and shared place attachment and place meanings. Numerous researches have focused on the sensory and instantly perceived components of sense of place, even though the majority of debates on this topic have acknowledged that it takes time to develop (Falconer, 2017). While researchers who study sense of place typically focus on its features that emerge slowly and over time, Raymond, Kyttä, and Stedman (2017) have discovered that some aspects speak to the quick and immediately arising perceptions of a place. So, in addition to place meanings

(i.e., collective, individual, and socio-cultural, as dealt with in hermeneutics or phenomenology) and place attachment (i.e., place dependence and place identity, as dealt with in positivism or post-positivism), the research tradition on sense of place has also taken into account perceived affordances (i.e., direct and contextual, as dealt with in scientific realism) (Raymond et al., 2017).
According to Newell and Canessa (2015), significant visual components and viewpoints that appeal to various stakeholders can be identified by viewing XR as platforms that interact with users' sense of location. As sense of presence facilitates cognitive processes through observation, which in turn enable XR to connect to people's sense of place through their subjective impressions and personal knowledge, sense of presence is also linked to sense of place in virtual reality (VR). As a result, sense of presence draws attention to XR as a medium and presents an intriguing viewpoint for evaluating how well a photorealistic XR serves as a communication tool. However, understanding the significance of sense of place—that is, place-based meanings and affordances—in relation to sense of presence is crucial for design objectives.

Figure 2. Shots of employing XR in different projects' activities. https://uk-mo.com/technologies/uk-well-placed-to-help-make-mainstream-xr-use-a-reality/

2.1 Sense of Place and Extended Reality XR

In studies of virtual environments (Zhang & Clear, 2015), mobile technology-assisted tasks, and augmented reality (AR) (Chang, et al., 2015), as well as in study settings connected to gamification (Bowser et al., 2013), the idea of sense of place has been explored. The research findings imply that these strategies enhance participants' or learners' sense of place, learning motivation, and learning achievements. The connection between XR and the sense of place has, however, only been examined in a few studies. (Newell, 2017).
A number of benefits are provided by virtual environments for design and architecture. Firstly, they provide a framework for integration, modelling and visualisation of many different layers of data from simulation of human behaviour (Mekni, 2018), through environmental hazards. They can also put design process participants and users in a position where they have easy

access to information and a shared spatial frame of reference (Li, et al., 2021). This permits the possibility of social elements being included in decision-making processes and is valid for both the participating experts and a larger audience. XR can add emotional engagement to collaborative design. These emotional engagement aspects become even more apparent when XR is used as a display technology rather than a screen (Mania et al. 2010).

2.2. Immersive Experience and Presence in Virtual Environments

The experience that virtual environment designers aim for is best described by the word "immersion" (Keil et al., 2021). While we are here focusing on immersive experiences created utilizing XR technology, it is important to note various types of immersion that are applicable to non-immersive scenarios. The primary distinction between presence and immersion is that the latter is regarded as a personal, psychological encounter, whilst the former depends on the technology being applied in a particular application (Nilsson, et al, 2016). Although the term "immersion" is ambiguous, it appears that in the domains of design research and development, it is most directly related to the system's technological fidelity. We shall use the term "Immersiveness" as a reference for this because Slater (2003) defined this type of immersion as "a technological feature, measure of the capability of a given system to replace physical space with virtual environment."
We think that the ability to induce this sense of presence and illusion of place is one of the features, which when implemented properly within XR design can greatly increase its usefulness. The immersiveness experience must investigate all facets of immersion to elicit a sense of spatial presence and an emotional connection to the environment in order to develop ways to engage space users in XR and spatial knowledge.

2.3. Narrative Immersion & Placemaking

A variety of perceptions of human spatiality are necessary for both narrative immersion and the placemaking possibilities it offers. The phrases "space," "place," and "sense of place" are used in both science and the humanities in various contexts. psychologists, writers, and virtual reality programmers all use these terms extensively in their work. Another issue that needs more focus is how precisely to offer such experience in practice. Especially when it involves adding XR display capabilities to a system, the idea that future technological developments can enhance immersion and thus offer a greater sense of presence is frequently assumed (Edler et al. 2018). According to Harrison., (1996), The human concepts of space and place relate to the structure of the world, the three-dimensional environment in which we inhabit. However, he contrasts cultural perceptions with those that frame innate human behavior in his theory of place (Naji, et al. 2018). According

to (Murray, 2017), There are four affordances for genres other than narrative, including procedural, interactive, encyclopaedic, and spatial affordances, which collectively promote new kinds of engagement and immersion.
The concept of place-making in the physical environment has been studied by Canter (1977) and Montgomery (1998) in (Fig. 3). Despite using significantly different methods, scholars have similar perspectives on three connected aspects in the physical environment.

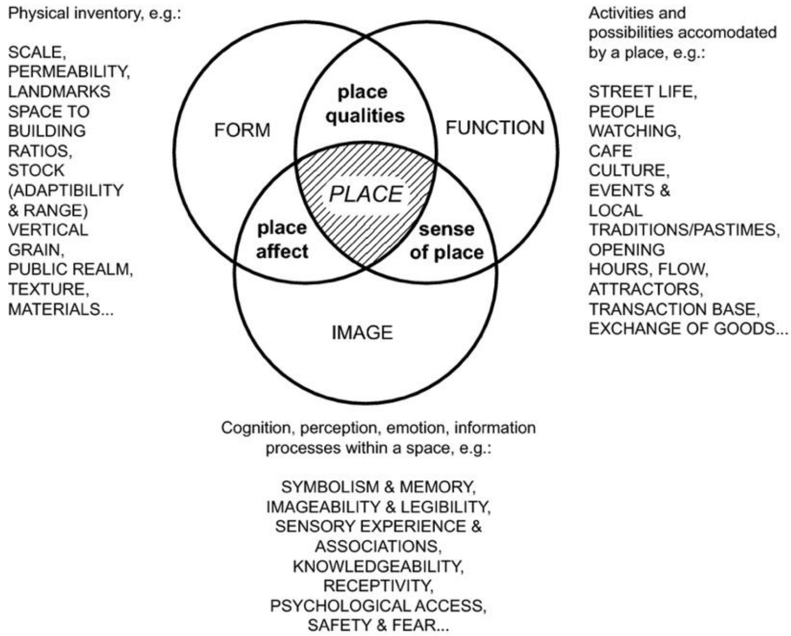

Figure 3. Dimensions of place with examples (adapted from Canter (1977) and Montgomery (1998)) and resulting concepts in bold (place qualities, sense of place, place affect).

According to Rapanotti et al., (2011), Virtual environment that make the experience more immersive include:
- Continuity of surroundings: The user must have continuity of the environment and be able to see in all directions.
- Conformance to human vision: Visual material must adhere to features that help people understand their surroundings, such as making far-off objects the appropriate size for our perception of their size and distance from us. Our perception of objects adjusts appropriately as our viewpoint shifts due to motion parallax.
- Freedom of movement: It's critical that the user have unrestricted movement inside the environment. That capability can be reached in room-scale VR and specially designed VR spaces, but it is impossible to attain in sitting VR and sophisticated technology is needed for stationary VR.

- Physical interaction: the user should be able to engage physically with virtual items.
- Physical feedback: To simulate a real-world interaction, the user should receive haptic feedback. In other words, when a user turns a doorknob, they not only mimic the motion but also feel as though they are holding the object in their hands.
- Narrative engagement: The user should be able to control how the story unfolds. Cues that encourage the user to come up with intriguing advancements should be present in the environment.

3D audio: XR environments must be able to accurately reproduce how sounds are placed in relation to nearby individuals and objects as well as the user's head position.

Therefore, our study shows how the concept of the immersivness of space can support the design of the XR experience by injecting acts of place-making along the design process. The focus is on how spaces turn into places which are bounded by their physical features; the individual and social experiences; and the narratives drawn from those experiences.

The potential of focusing on narrative immersion and literary placemaking in XR is discussed to evoke a stronger sense of place and a feeling of presence and belonging in users.

3. Methodology

A mixed methods study approach was conducted to gather qualitative data, including exploratory pilot study accompanied by an experiment and a questionnaire-based participants opinion survey. In order to develop the framework, an analytical study for the most significant space characteristics that affect the user experience and emotional state, place making elements and space presence properties was considered. (Table 1). A questionnaire was created to see how users would respond to aspects of an XR environment setting of the Grand Egyptian Museum. A 3D model of spaces was designed to be used as the interaction environment in order to provide visual stimuli capable of provoking arousal responses during users' navigation of the virtual environment VE, in particular zones where spaces were designed to surpass their neutral responses.

TABLE 1. Elements of the XR experiment (Immersiveness, place-making, spatial properties).

Immersiveness Criteria	**Elements of the Place-making**	**Spatial Presence Properties**
Continuity of surroundings	Events	- Familiarity - Presence - Illusion
Conformance to human vision	Relative Location	- Resembles actual Space - Boundaries (Dynamic and Fluid) - Not Actually 3D
Freedom of movement	Authenticity	- Complex meanings
Physical feedback	Adaptability	- Problems can be controlled
Narrative engagement	Varity of Experiences	- Duplicable
3D audio	Transition	- Complex Connections
	Memorable	- Defined Cues - Visual Identity
	Gestures	- Meaning/ Concept Focus
	Graphic Representation	- Presence - Mental Representation

A total number of 60 volunteers aged between 20 and 45 (30 male and 30 female) with diverse background were randomly assigned to the experiment. The participants indicated no physical or mental conditions that would preclude them from taking part in the study, and they had normal eye-vision. Participants performed a 3D-pointing task and were selected upon the fact of making a prior physical visit to the Museum. The evaluation included the effect of combining audio and visual rendering. Spatial presence and its components were evaluated using the ITC-SOPI questionnaire which focus on users' experiences (Lessiter, Freeman, Keogh, & Davidoff, 2001). In addition, objective metrics based on user performance and behavioral indicators were logged.

Figure. 4 Samples of 3D visualization of the Grand Egyptian Museum used in the experiment.

4. Study Limitations

Methods of using physiological measurement tools tests such as eye-tracking, electrodermal activity (EDA), and electroencephalography (EEG) were not included in this study.

5. Results & Discussion

According to Participants responses, we were able to detect factors that have the biggest impact on enhancing the immersiveness, placemaking and presence in XR experience.

TABLE 2. Immersiveness results as perceived by participants (Author).

Immersiveness Criteria	Continuity of Surroundings	○
	Conformance to human vision	●
	Freedom of movement	●
	Physical feedback	●
	Narrative engagement	●
	3D audio	●
Elements of the Place-making	Events	●
	Relative Location	●
	Authenticity	●
	Adaptability	○
	Varity of Experiences	●
	Transition	●
	Memorable	●
	Gestures	●
	Graphic Representation	○
Spatial Presence Properties	Familiarity	●
	Presence	●
	Illusion	●
	Resembles actual Space	●
	Boundaries (dynamic and fluid)	●
	Not Actually 3D	●
	Complex meanings	○
	Problems can be controlled	●
	Duplicable	●
	Complex Connections	●
	Defined Cues	●
	Visual Identity	●
	Meaning/ Concept Focus	●
	Presence	●
	Mental Representation	●

In this study, we investigated how to combine narratives of placemaking and XR to create a more engaging experience for the user in line with the objectives of digital development and to boost stakeholder participation in the design processes. This study goes a step further by looking at a small "Cyber space" of examples to look at the integration of XR technologies in the area of placemaking and immersiveness. Our suggestion is to solely use high fidelity XR spatial data. The built environment, with its system of spatial laws and interactions, is the most important component of XR, as Chen and Lin (2018) pointed out. People are also used to interpreting spatial cues from their senses and through the mediating effects of more emotive and humanistic ideas like feeling of place and place attachment. The framing of our spatial perceptions and actions requires meaningful places when building virtual environments intended to encourage involvement and engagement with communities and members of the public when confronting design challenges, Dawkins and Young (2020) made the case that it is crucial to preserve both contextual and affective links to physical places.

Virtual non-places frequently have little emotional impact on users, which hinders their capacity to feel present—as though they are in a different world and location. It might be argued that this also affects participants' willingness to fully immerse themselves, which leaves out the essential elements of presence and embodiment. In addition, as present technology is far from achieving the immersiveness of the typical spatial experience, which involves the complete range of senses, the worlds fabricated within virtual environments are always imperfect when compared to "reality." For applications like VR gaming, this flaw is less important, but when building environment representation is the primary objective, the situation is very different. Because we aim to facilitate knowledge of complex processes and relationships that occur in a material world, we must develop a high fidelity XR. This deeper understanding depends heavily on immersion and presence.

6. Conclusion

Immersion is beneficial for the learning process, we propose applying narrative immersion tactics identified in placemaking to improve the virtual placemaking competencies, as illustrated in the case study. It is critical to create semantically systems that provide a space for meaningful interactions with the virtual model that are place-based methods which can be employed in users' daily interactions with the physical world. We recommend to incorporate narrative immersion into the creation of XR in order to increase stakeholder involvement in design processes. Additionally, there is a vast research agenda to be investigated in this regard: How much immersion in XR do we actually need, and when? How are immersion and presence affected by fidelity to the environment? How can we provide social presence in addition to physical presence? Is the sense of place created by VE the same as that found in the physical world? To fully realize the potential of XR, those and much other questions are worth investigating. By presenting narrative placemaking as a useful tool in the current development of high fidelity XR that can be applied in design processes, we hope to advance conversation on such issues. We may draw the conclusion that sense of presence and sense of place both serve as helpful conceptual frameworks for comprehending XR-related sensations to enhance communication in design processes, and that these two frameworks interact with one another. In addition, we showed how previous familiarity, or prior awareness of and/or a prior visit to the relevant site, changes people's perceptions of presence and place. The varying viewpoints on the preferred design outcome are also somewhat related to the differences in respondents' levels of familiarity. The sense of presence provides data on how useful and successful the medium was at providing insights into the location and its features. The study shows that perception depends not only on the degree of realism that a 3D representation can convey, but also on the audience members' specific knowledge, prior experiences, and unique features. A 3D visualization, on the other hand, might reinforce any potential existing meanings while delivering information, affordances, and even meanings of a place. Our findings indicate that photorealistic 3D representations are most effective when used in conjunction with real-world visits and as supportive tools in design communication.

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6.B.

VIRTUAL REALMS AND MULTIVERSE ENVIRONMENTS - III

INTEGRATING AI IMAGE GENERATION TO FIRST-YEAR DESIGN STUDIO: “INVISIBLE CITIES” REIMAGINED WITH AI SUBTITLE

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Abstract. AI technology has been widely used for image generating during the design process both in academia and industry. There are hesitations to integrate AI image-generating software into design education due to copyright and ethical issues. However, its spread is inevitable, and students should be aware of the pros and cons of using AI technologies. Hence, this study aims to examine the effect of AI image generators on the design process of first-year design students. Passages from Italo Calvino’s book “Invisible Cities” were given to the students, and they were expected to work in groups of 2-3 to design 3D physical models abstracted from the scenarios by the book’s utopian cities. Since AI image generators work based on text prompts, the students extracted keywords from the book’s chapters to generate images. With the support of the images generated by the AI image generators, they developed final visuals and abstract physical models of utopian cities. Based on the outcomes, we observed that AI image generators were used for three main goals by the students: (1) spatial organization, (2) details of the modules, and (3) abstraction/realization of the spatial atmosphere. Based on this analysis, we discussed the role of AI image generators among the polars of being a tool and co-designer in the design process.

Keywords: AI image generation, design education, design studio, invisible cities, AI in design education.

ملخص. تم استخدام تقنية الذكاء الاصطناعي على نطاق واسع لتوليد الصور أثناء عملية التصميم في كل من الأوساط الأكاديمية والصناعة. هناك تردد في دمج برامج الذكاء الاصطناعي لتوليد الصور في تعليم التصميم بسبب حقوق النشر والقضايا الأخلاقية. ومع ذلك، فإن انتشاره أمر لا مفر منه، ويجب أن يكون الطلاب على دراية بإيجابيات وسلبيات استخدام تقنيات الذكاء الاصطناعي. ومن هنا تهدف هذه الدراسة إلى دراسة تأثير مولدات

الصور بالذكاء الاصطناعي على عملية التصميم لدى طلاب التصميم في السنة الأولى. تم توزيع مقاطع من كتاب إيتالو كالفينو "المدن غير المرئية" على الطلاب، وكان من المتوقع منهم العمل في مجموعات مكونة من 2-3 أشخاص لتصميم نماذج مادية ثلاثية الأبعاد مستخلصة من سيناريوهات المدن الفاضلة في الكتاب. وبما أن مولدات الصور المدعومة بالذكاء الاصطناعي تعمل بناءً على المطالبات النصية، فقد استخرج الطلاب الكلمات الرئيسية من فصول الكتاب لإنشاء الصور. وبدعم من الصور التي تم إنشاؤها بواسطة مولدات الصور المدعومة بالذكاء الاصطناعي، قاموا بتطوير صور نهائية ونماذج مادية مجردة للمدن الفاضلة. بناءً على النتائج، لاحظنا أنه تم استخدام مولدات صور الذكاء الاصطناعي لثلاثة أهداف رئيسية من قبل الطلاب: (1) التنظيم المكاني، (2) تفاصيل الوحدات، و(3) تجريد/إدراك الغلاف الجوي المكاني. بناءً على هذا التحليل، ناقشنا دور مولدات صور الذكاء الاصطناعي بين القطبين كونها أداة ومصممًا مشاركًا في عملية التصميم.

الكلمات المفتاحية: *توليد الصور باستخدام الذكاء الاصطناعى، تعليم التصميم، استوديو التصميم، المدن الخفية، الذكاء الاصطناعى فى تعليم التصميم.*

1. Introduction

Artificial Intelligence (AI) is rapidly improving technology that interests the practice of design and architecture. Considering the fact that academia and industry feed each other, AI will affect design education as well. Design education represents a complex study area mainly due to the issue of transferring tacit knowledge. There are variables such as studio environment, teachers, students, etc., and various approaches exist in the design studios, such as master-apprentice, user-designer, and peer critiquing (Oh et al., 2013). Hence, *design studio* involves different kinds of interactions between students as well as between students and teacher(s). Moreover, these communications can be extended to be amongst students and machines with the integration of AI (Akçay Kavakoğlu et al., 2022). In other words, machines are already part of the design process. In this study, we aim to investigate the role of AI image generators in the design process through a first-year design studio project.

Recently, many industries have been facing rapid technological improvements in digital visualization, especially with the integration of AI and AI research about design improved efficiency (Belem et al., 2019). While some approaches are positive with this integration, some scholars are doubtful, especially considering its effect on design professions and education. According to Başarır (2022), this continuous development in design representation is similarly experienced with Computer-Aided Design (CAD) and Building Information Modeling (BIM), relatedly design education will have to participate in the adaptation process of this technology. Indeed, CAD has been changing designers' approaches as well as design education. Considering the fact that representation plays an increasingly crucial role in the creative processes (de Vries & Masclet, 2013), many design schools teach CAD during undergraduate education by adapting to this transformation. To understand the deployment for AI image generation, we aimed to study this issue with first-year design students since they would not have any experience with former digital design tools. Thus, we could see the raw approaches of students to this type of software, which is more capable than CAD and BIM software in producing images in terms of quality and quantity in a shorter time.

In this study, though students were encouraged to use AI-image generation in the last phase of the project. Primarily, it is aimed at students using physical models, learning by making (LBM) approach, and paper-based design thinking (PDT) through 2-D visual representations. Thus, we aimed to give students a wider range of creative techniques, starting from traditional techniques and ending with the most recent ones. Since the first-year education at Istanbul Technical University allows a curriculum where industrial design, interior architecture, and architecture students learn in the same courses, we intended for students to freely select their tendencies toward design within the project by choosing the passages from the book "Invisible Cities" (Calvino, 2010), which has a language that opens up discussion and interpretation for designing for different scales and mindsets. Subsequently, we analyzed the use of AI within the student projects for further discussion about where to position AI image generation software among different perspectives in the literature.

2. Literature Review

Artificial Intelligence (AI) is meant to define the intelligence that machines, mostly computer programs, have; it is an umbrella term that includes deep learning, machine learning, and language processing. It is considered a competent technology with various diverse application areas, from natural sciences to art. AI is capable of creating ideas and concepts such as "recognizing, summarizing, translating, predicting, and generating text and other content based on knowledge gained from massive datasets (Jonson, 2023)." The input given to AI can be text; however, some generators also use images as inputs. Moreover, this practice has also produced professional fields such as -prompt artists or engineers- who are experts in dealing with AI image generators. Indeed, AI is better than humans at performing specific tasks, and for the designer, using computers or algorithms while making art or design is not new at all. Frieder Nake produced an artwork using a specific algorithm in 1967 (Hodge, 2016). Based on Dietrich's article (1968), it can be understood that what Nake did in those years was highly complex. During these years, he used equipment, including a Zuse

Graphomat Z64 electronic tape-punching machine, a Graphomat Z64, and a drawing machine (Hodge, 2016).
Moreover, during the 1970s and 80s, AI-generated art technology has already been used with Computer-Aided Design (CAD) methodology (Kundu, 2022). CAD is a methodology that improves the designs in an artificial 3D environment. Hence, the designers and artists could see the real-time results on a computer when they changed something on the actual product. During the 1990s, the entry of CAD technologies into the design world scared many scholars due to their capability of replacing them. However, now we see CAD as a tool for supporting design, and there are studies to enhance its engagement in design processes.

What AI image generators do is based on a framework called Generative Adversarial Networks (GAN) based on machine learning technology (Goodfellow et al., 2014). According to Huang and Zheng's (2018) study, there is no need to use a large number of images to produce architectural layouts using GANs. Moreover, using GANs for generating environments is successfully improving (Chaillou, 2019). On the other hand, different visual production methods started to be developed in this process. Isola et al. (2017) developed a method for generating images from sketches. Thanks to this method, Pix2Pix, it was possible to transform day into night or obtain realistic images from drawings. In this approach, which is based on the gradual augmentation of GANs, new layers are added to the generator and discriminant networks in stages, increasing the image accuracy and quality (Karras et al., 2018). Brock et al. (2018) established a system that can produce natural images with their work called BigGAN. They developed the latest methods in the image synthesis stage by combining novel approaches such as truncation tricks and class-conditional batch normalization. Karras et al. (2019) aim to create various high-quality images with a structure that uses the manufacturer network, which they call StyleGAN. They showed that lifelike faces can be produced thanks to the power of GANs.

With the gradual progress of the studies and the establishment of the theoretical infrastructure in the background, it was possible to create products that the end user could experience. This way, design ideas and concepts can be produced visually and with commands over online platforms. There is still much development needed in visual production with artificial intelligence, and one of the essential sources of data and demand for this development will be design students. Adding artificial intelligence to a well-defined architectural education is difficult, especially to upper-class projects. There are several reasons for this. The first reason is that the visual outputs produced by artificial intelligence tools may contain various errors and give different results from the user's prompts. The other reason is the difficulty of determining the place of artificial intelligence in the upper-grade project course, whose process and outputs are already clear. For certain reasons, the study was conducted with first-year architecture faculty students.

There are studies on how AI affects architectural design and how architects and designers adapt themselves to the improvements in this technological realm. For example, Tamke et al. (2018) described cases where machine learning influences architectural design by implicating the need for novel design structures for a better application of AI for architecture. Tamke et al. (2018) studied machine learning and artificial intelligence using the LaceWall program. The suggested machine learning-based approach displays neural networks' capacity to classify the shape of intricate geometries using high-dimensional discretizations with a wide range of input parameters. The proposed method's ability to allow and give sensitivity when it is necessary to classify unknown data is its key strength. The study also emphasizes the significance of the data's source, volume, and quality. In contrast, Cudzik and Radziszewski (2018) examined AI tools in architectural design while keeping the architects in control of decision-making processes. The solution to the issue of closing the gap between architecture and machine learning technologies can be found within architectural design education (Khean et. al, 2018). Because academia and industry feed each other continuously, AI improvements should also affect design studio education, and indeed, scholars have studied how AI can affect designers and design methodologies empirically, even though there is no consensus or framework about how it should be formalized. In the context of the design studio, Akçay Kavakoğlu et al. (2022) studied the application of AI in early architecture education involving AI in the creative processes. Her study aims to include AI as a creative agent in design by making the creative process collaborative. Similarly, Başarır and Erol (2021) analyzed the integration of AI into architectural design by briefing AI directly from the client's prompts. Moreover, Başarır (2022) conducted a study with first-year pupils aiming to find ways to adapt architectural education considering the improvements in AI, whereas focusing on representation, Tong et al. (2023) studied the integration of AI-based techniques into first-year design education within a visual communication course. Following these studies, aiming to contextualize the role of AI image generation in the design studio, we developed an empirical study with first-year students.

3. The Study: 'Invisible Cities' Reimagined

This research focuses on the design project of first-year design students implemented within the scope of the 'TES Foundation Studio, Project II course' in the second semester at ITU as a case study. 'TES Foundation

Studio' is an educational system applied at Istanbul Technical University, and it allows first-year students of the faculty of architecture, interior architecture, landscape architecture, urban planning, and industrial design to study collectively for two semesters. As part of the TES Foundation Studio, our team, Section 6, includes students from three departments: architecture, interior architecture, and environmental design. This diversity allowed students to be educated in a blended environment in terms of scale in the first year. So, the first-year design studio bears a substantial potential for applying our study to evaluate the role of AI in design education with a more holistic understanding since the students do not tend to design with pre-conditions. Also, as authors with different professional backgrounds, we had a chance to discuss the role of AI in the design studio from various perspectives with our diverse tendencies about scale factor. Hence, we have selected the book passages from 'Invisible Cities' that may not limit students in terms of scale. Within the scope of the TES Project II course, we planned a three-week project, "Invisible Cities Reimagined" (see Table 1). The students developed the projects using traditional creative techniques for the first week and a half. After the students had learned their passage from the book, they extracted keywords with rough sketches using PDT and carried on with physical models using LBM as their next assignment. When the designs reached an acceptable level around the midst of the project, the AI image generation tool (dream.ai) was introduced by an expert academic. After that step, the students used all the techniques they learnt to finalize their projects.

TABLE 1. Timeline of the study.

WEEK	DAYS	DESIGN APPROACH	CONTENT
W1	**Day 1**	**Paper-Based Design Thinking (PDT)**	Introduction to **P1_ *Invisible Cities* Reimagined** [Groups of 2-3] **Submission**: Ideas on paper through sketches and keywords
	Day 2	**Learning by Making (LBM)**	**Submission:** Representing the city as a physical model (20x20x5 physical model)
W2	**Day 3**		**Submission:** The Axonometric drawings of the cities (1/500)

	Day 4	**Design process with the involvement of AI Generator**	Workshop on Generative AI (dream.ai)
W3	**Day 5**		Critiques on the whole set of representations **Submission:** The project poster w using generative AI
	Day 6		**Final Submission**

The main objective of the assignment "Invisible Cities Reimagined" was to design representative urban structures with the involvement of AI generators based on the scenarios inspired by the book "Invisible Cities". Based on this primary objective of the project, our didactic objectives were to:

- develop the designing and critical thinking ability of the students;
- sharpen research and analytical problem-solving skills on a given planning/design problem;
- expand graphical representation and form-generating skills learned in visual communication courses as well as team-working ability.

These objectives are selected among the learning outcomes of the Foundation Studio's planned learning outcomes.

One of the primary reasons behind the book selection is that it includes fictitious city descriptions with several conceptual and physical definitions. The book includes 55 imaginary cities depicted in experimental and perceptual aspects. Students could re-script the whole city life and the related physical environment with abstract expressions and the gaps in the narratives. Additionally, considering the AI image generators are trained with text prompts and keywords, it was significant to utilize book passages as a design datum. Eight passages consisting of Thin Cities 2 (Zenobia), Thin Cities 3 (Armilla), Cities&Eyes 1 (Valdrada), Thin Cities 4 (Sofronia), Trading Cities 3 (Eutropia), Cities&Eyes 1 (Baucis), Cities&The Dead 4 (Argia), and Trading Cities 5 (Esmeraldina) from the book "Invisible Cities" were chosen and assigned to student groups. The city descriptions were transformed into physical models by interpretations of the book's narratives. Following, student groups created AI-generated images extracting words from the book passages related to their design ideas represented in the physical models.

4. The role of AI image generation in the design process

Within the scope of the assignment 'Invisible Cities Reimagined,' students were divided into 27 groups, and every three groups worked on the same city narrative. To scrutinize the role of AI software in the design process, we selected 19 projects, considering the groups' capacity to improve the project by integrating AI image generation techniques. The student groups are denominated based on the city names for further analysis (see Table 2). Some analyzed groups did not state the prompts they used to train the software, although they presented AI-generated images on their final sheets. Hence, the data we collected from the students is based on their final presentation sheets, which included AI-generated images, the prompts used for the image generator, visuals of the physical models, and sketches based on the given passage from the book.

TABLE 2. Assigned Cities and Groups.

City	Group
Thin Cities 2 (Zenobia)	TH2-G1
	TH2-G2
	TH2-G3
Thin Cities 3 (Armilla)	TH3-G4
	TH3-G5
	TH3-G6
Cities&Eyes 1 (Valdrada)	CE1-G7
	CE1-G8
Thin Cities 4 (Sofronia)	TH4-G9
Trading Cities 3 (Eutropia)	TR3-G10
Cities&Eyes 1 (Baucis)	CE1-G11
	CE1-G12
	CE1-G13
Cities&The Dead 4 (Argia)	CT4-G14
	CT4-G15
	CT4-G16
Trading Cities 5 (Esmeraldina)	TR5-G17
	TR5-G18
	TR5-G19

The primary outcome of our analysis was revealing how students use AI image generators for their project. Based on the analysis of the student project outcomes, and the general approach of the students to using AI tool. we categorize the student approaches to use of AI in the design process under three headings: *spatial organization*, *details of the modules*, and *abstraction/realization of the spatial atmosphere* (see Figure 1). In every analysis stage, the physical models and AI images were compared to understand how the designs evolved when AI software was integrated. In this section, we described these approaches to the integration of AI by the students.

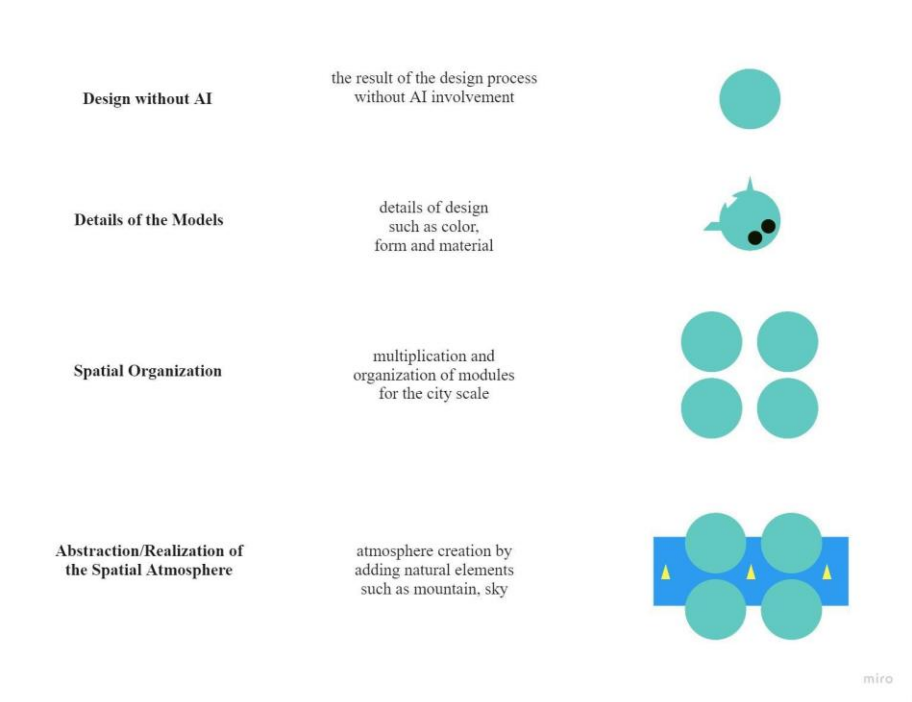

Figure 1. Categorization of the role of AI in the design process

4.1 SPATIAL ORGANIZATION

As a complementary aspect, spatial organization plays a substantial role in design. A successful spatial organization involves elements that exist in a visually appealing and functional composition. One of the primary reasons we included spatial organization as a sub-topic is that it applies to various design disciplines, including architecture, interior design, and industrial design. For this student project, the spatial organization represents aspects such as the overall layout of the city, the relationship between the city modules/elements, and the flow of space, forming a meaningful whole.

Looking at the projects collectively, each physical model has organizational integrity to some extent. However, when individually examined, very few of the physical models were actually designed by taking into account the internal structure of the cities. The initial action regarding the design of the fictional cities was to understand and interpret the city parts. These parts were addressed as *modules*. Project scale, material use, and project duration were significant limitations, and the students struggled to create variations and multiples of the designed modules. AI came as a subsidiary agent herein. Since the groups did not utilize the resulting image or add parts to their physical models as the AI image instructed, it would be incorrect to regard AI as a co-designer under this topic. However, AI's work as a creative agent on this issue is a non-negligible fact.

AI's use/effect on a spatial organization can be categorized under two subtopics: multiplication of the same module and combining more than one city structure with a particular system. Eight of the student groups used AI to produce an image that included multiples of their single module. In Figure 2, it can be seen that AI produced variations to the modules, and in Figure 3, it can be seen that AI studied how the same or different kinds of modules can come together. There also are examples of where the material (which will be underlined in the following chapter) and structure were altered by AI to create meaningful connections between the modules (Figure 2).

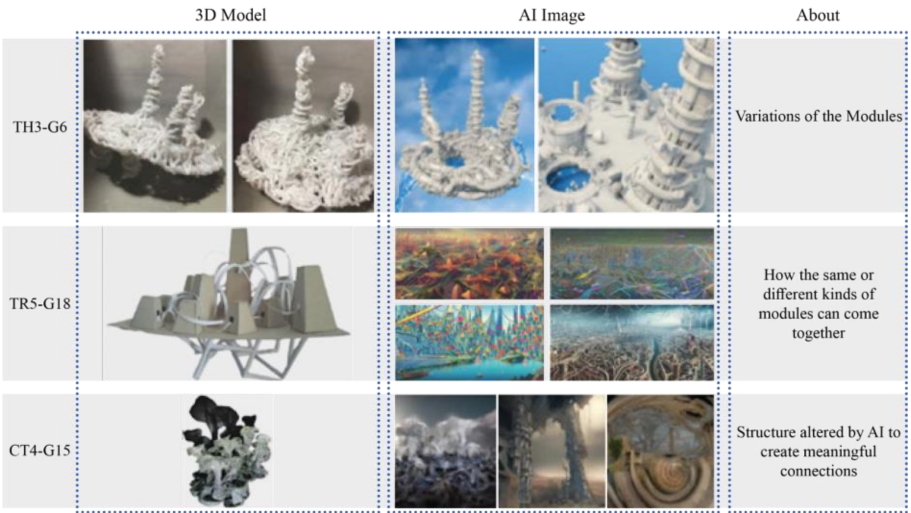

Figure 2. Student physical models and related AI images showing how the AI altered modules and their connections.

The book describes cities formed by the merger of smaller cities. The urban organization of those cities is a composition resulting from the combination

of the minor, self-operating city structures. Therefore, it is only meaningful when these larger cities are presented with subunits. TH4-G9 physical model shows a spiral structure that works as a spine for two half-cities with different themes (Figure 3). The related AI image reveals the combination of overlapping spiral rails and a new city structure born out of it.
Similarly, the TR3-G10 physical model bears a Möbius strip base structure and nine sub-cities mounted on the strip (Figure 3). Out of the three AI images the group produced, the third image has a spiral path going in and out of the landscape. Although there are no direct relations to the image, the group's choice of the renowned -but particular- geometry for their physical model is based on the non-orientable feature derived from the strip. Through this unique geometry, the students were able to separate the small living areas (which are *on air*, *underwater*, and *on the ground* according to their AI text prompts) and provide continuous circulation.

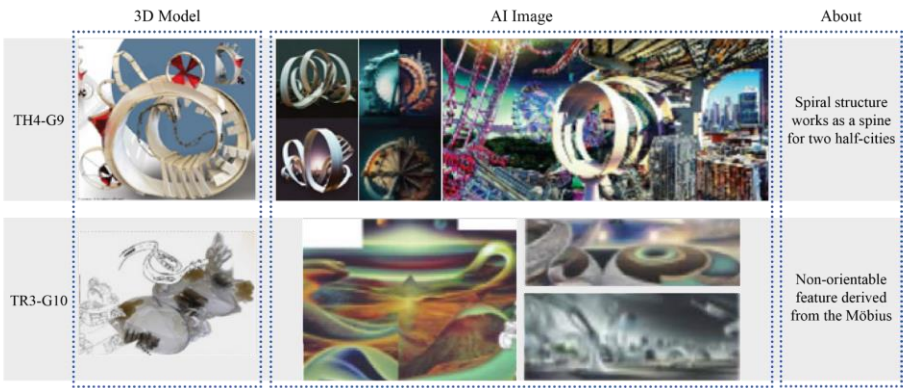

Figure 3. Student physical models and related AI images showing how the AI studied the urban structure and texture.

4.2 DETAILS OF THE MODULES

When we review the initial versions of the student works preceding the AI image generator being integrated, it is seen that the students created the physical models in an abstract style. This approach can be due to several limitations, as mentioned above, such as implementation problems, high costs, and the inability to provide some materials. Also, the fact that the students generated their physical models at the earlier stage of the design process and, in a short period, caused them to produce undetailed physical models. At that point, the AI image generator enabled students to represent their city designs in an exhaustive manner by elaborating the modules. Within the context of 'Detailing the Modules', the city designs are mainly developed in three primary aspects, one of which is creating more detailed forms displaying interiors, structure, and complementary elements; others are diverse color and material usage, see Table 3.

TABLE 3. Categorization of the 'Detailing the modules.'

Form	• Interior details of the modules • Complementary details • Structural details
Material	• Material selection for rough physical models
Color	• Alternative color usage

Students commonly utilized AI software to illustrate interior spaces from several perspectives and fill the unconceived parts of their designs. Most of the physical models consist of shells, unlike AI images depicting internal structures of the cities, like urban spaces, connection routes, and defined living interiors. For instance, while the physical model of group TH2-G1 shows the rough form of the module constitutive of the whole city, the AI image shows the details within the spheres (see Figure 4).

In other respects, interior images created with keywords derived from the same book passages are very similar in terms of details, materials, and general spatial atmosphere. The AI-generated interior image and the physical model of the group CT4-G16 correspond to each other regarding material usage (see Figure 4). On the contrary, while the physical model of group CT4-G14 does not consist of any lithic material like stone or clay, the AI-generated interior image of the same group presents a rocky texture similar to the group CT4-G16's visual (see Figure 4). Even though the exterior forms of these designs are very different and students had diverse design ideas initially, the AI image generator creates similar interior depictions with similar prompts and keywords. In the end, both interiors are reminiscent of "worm tunnels and crevices" full of clay as literally defined in the book passage.

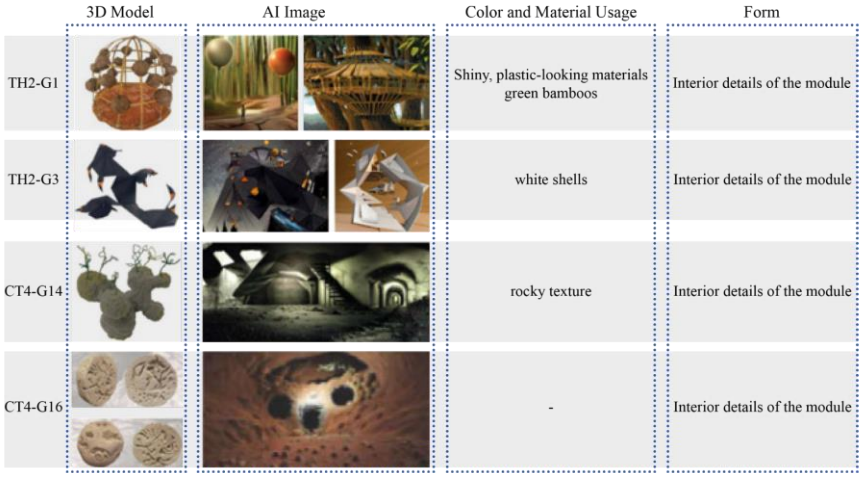

Figure 4. Interior details of the modules with the integration of the AI software.

On the other hand, some groups enhanced their city designs by adding complementary and structural details with the integration of AI software. Student groups that formed their cities at a sufficient level by working on physical models benefited from the AI image generators not only for demonstrating exact images of interiors but also for proposing a more familiar cityscape using several realistic elements such as windows, metal frames, and glass materials. Additionally, the minor parts of the urban systems, such as connection routes, bridges, and living areas being formed simply in the physical models, are concretized with the clear portrayal in the AI software. As seen in Figure 5, the physical models of the student designs represent the urban texture as an outline. Followingly, AI images of the cities enlighten the figure-ground relations of the urban system by defining the internal elements explicitly. Even though the AI-generated images do not provide remarkable alterations to the designs' forms, they help strengthen the connections between the modules, crystalize the structural appearance of the elements, and create a meaningful city view as a whole.

Figure 5. Complementary and structural details with the integration of the AI software.

Moreover, AI-generated images of the cities are easily distinguished by their intense color and material usage. In groups TR5-G18, TH2-G2, and CE1-G8, AI images provide diverse versions of their physical model, both material and structure-wise (see Figure 6). These enable students to improve the visual representation of their city designs. Altering the colors and materials quickly also brings about the advantage of getting the most appealing design appearance in a short span of time. For instance, in group TR5-G18, students carving out an achromatic physical model presented several color options through AI software. Further, the group TH2-G2 gets a dramatic scene of the city with a blue skylight effect on the image (see Figure 6).

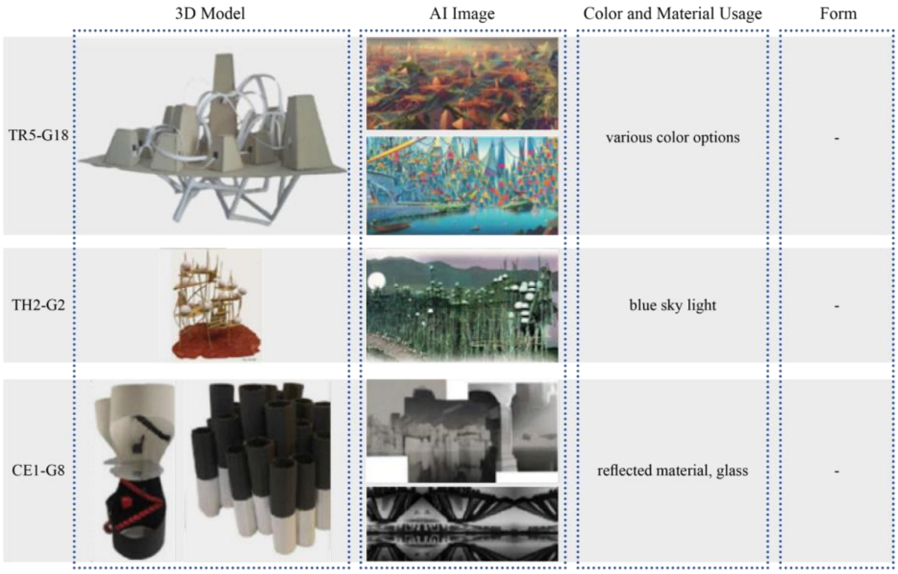

Figure 6. Color and material usage with the integration of the AI software.

4.3 ABSTRACTION/REALIZATION FOR SPATIAL ATMOSPHERE

With the involvement of AI in the design process, we observed that students increased the quality of their final images by making them either more realistic or abstract. To perform this approach, students added elements such as sky, mountain, or background images that complement their design by making the audience feel the atmosphere of their city. In that sense, this is not to make it real or abstract but rather more *diegetic* by leaving some design decisions to AI.

For instance, TH2-G1's physical model does not give any idea about the scale or the atmosphere of the city (see Figure 7, left). Hence, the group improved the atmospherical feeling of the city by locating the city on the ground, producing a view using the AI. Moreover, the group used "bamboo on dryland" and "balloon houses on bamboo" to improve the spatial atmosphere, and the human figures used by the group also strengthened the atmosphere and let the audience understand the scale.

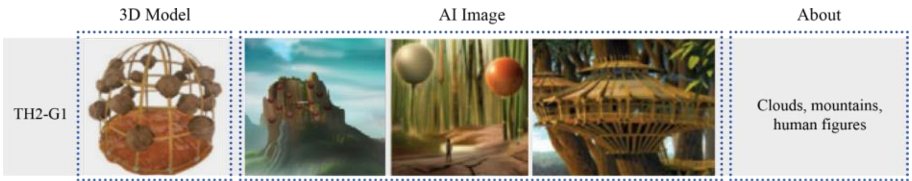

Figure 7. TH2-G1's physical model (left), AI image (right).

One of the reasons behind the title's name, which includes both realization and abstraction, is that the described cities are open for both. For example, TR3-G10 abstracted their city's appearance by giving prompts such as to the AI image generator "galaxy, surreal, Mobius, twisted mountains," which was not included in their given text. However, by following this method, they reflected the city atmosphere that they designed for (see Figure 8). Indeed, this group believed their atmosphere should be terrestrial, and they used AI to complement the look. Another example of abstraction can be seen in the project of TH4-G9; in their project, the use of AI image generation emphasized the spatial atmosphere by adding a dimensionless city background (Figure 8). Thus, TH4-G9 and TR3-G10 designed their cities to be more abstract, and the use of AI improved this feeling in their work.

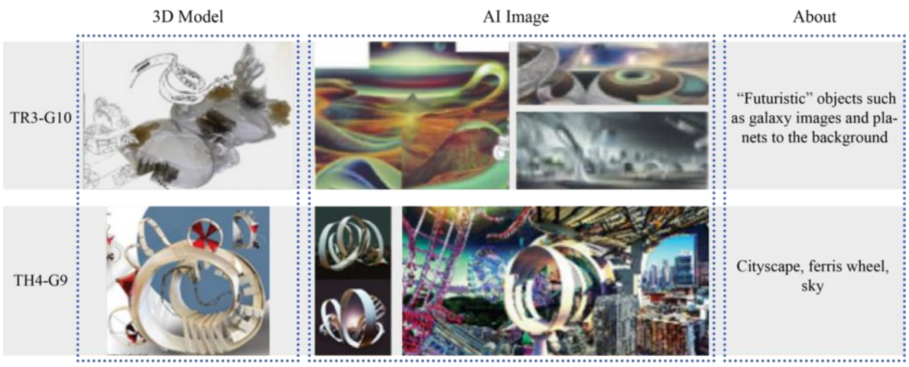

Figure 8. TR3-G10 and TH4-G9's AI image, the combination of physical models and sketches.

From a different perspective, TH3-G4 combined AI images and their physical model photos, and to enhance the feeling of the forest atmosphere, they used the AI image generator to blend a forest into the city structure (see Figure 9). Although the group attempted to merge a tree image into the image of the physical model, it only gave an idea about the scale but not the atmosphere as it was with the forest in the upper image. Other than that, the students used water and sky as complementary atmospheric elements in their visualization, which was produced with the help of AI. Figure 9 shows the difference between CE1-G7's AI images and the physical model; in the physical model, they struggled to materialize water, whereas, with their AI images, water and sky emphasize the value of their city, which is directly related to water and reflections as it is explained in the book. Here, the students used AI image generation effectively, where their skills fell short.

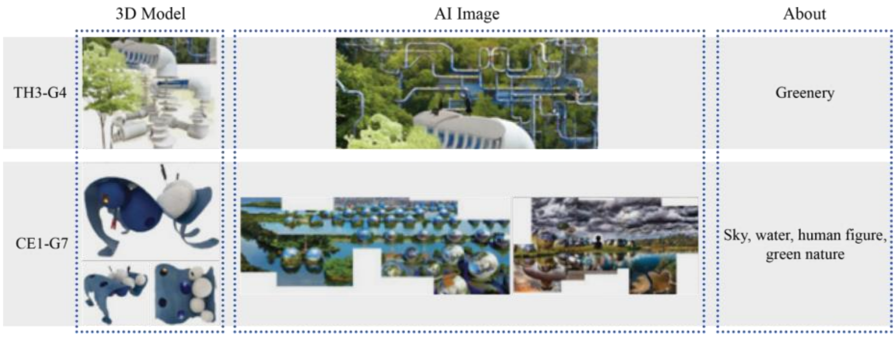

Figure 9. TH3-G4 and CE1-G7's physical model and AI images.

4. Discussion and Concluding Remarks

The students mainly utilized AI software to complete the missing parts in their designs. Multiplying the modules to form an image of a city and urban texture, and creating interiors in detail, are among AI's essential roles in the design process. Although the book passages, which are the base of the designs, portray fictitious cities; while the students created physical models with a more abstract approach, they tried to put their designs in a realistic atmosphere with the integration of AI. They also placed their modules on natural surroundings and city views using background images. Relatedly, students utilized AI image generation technology for their projects by following three main design approaches: spatial organization, details of the modules, and abstraction/realization for the spatial atmosphere. To compare our study with the existing literature we observed two different approaches to AI within the design process:

- (1) including AI as a creative agent in the design process: Akçay Kavakoğlu et al. (2022) studied the application of AI in early architecture education involving AI in the creative processes. Her study aims to include AI as a creative agent in the design by making the creative process collaborative, and she aims to include the communication between students and machines as part of the design process as an addition to the student-student and student-teacher interactions.
- (2) using AI as a tool similar to CAD and BIM in the design process: Başarır (2022) stated that the continuous development of representation was experienced similarly to Computer-Aided Design (CAD) and Building Information Modeling (BIM). Thus, AI image generation can be another robust design tool like them.

In this study, we analyzed that the students utilized AI algorithms somewhere between these two definitions; they used AI as a complementary tool (see Figure 10). To discuss the approaches, *spatial organization* was the least creative; whereas for the other two approaches, *details of the modules* and *abstraction/realization (spatial atmosphere),* AI was closer to being a creative agent.

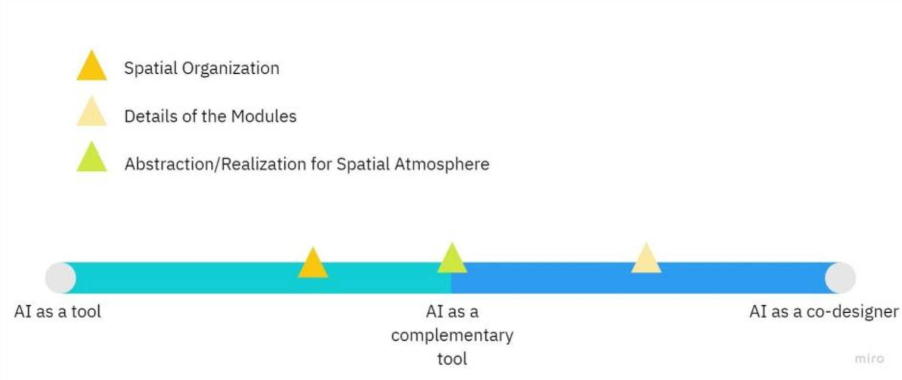

Figure 10. AI's placements in the students' design processes.

For the issue of spatial organization with AI image generation, students were not successful in benefiting from the generated images effectively. Thus, even though AI was used as a creative agent, students' skills in integrating AI into their project were insufficient. When the students used AI image generation to emphasize spatial atmosphere, design decisions were left to the generators, but these were mostly complementary. The students already took the main decisions themselves but they got support from AI as a tool that increases visualization. Hence, AI was closer to being a tool for *realization/abstraction of spatial atmosphere.*

Whereas for *detailing of the modules*, AI was the most active as a co-designer. Even though there is a lack of quality in image production, generated images successfully fill the areas that students could not even have the time to consider as part of their designs.

We see that some possible improvements and limitations are necessary to state. First, most of the students in the studio have yet to work with AI tools. Students who used AI tools before were curious and produced uncontrolled results. Therefore, they must familiarize themselves with AI visualization interfaces, processes, and software. Many students can write their requests in paragraphs. Nevertheless, AI tools allow limited prompts. Due to the word constraint of AI tools, it took time for students to understand with which prompts the desired image could be produced.

On the other hand, AI tools allow for iterative enhancement of the selected image. However, the students considered the visual alternatives they obtained due to the first prompts they wrote as the final product. Although it was stated that the images they chose could be edited with the help of new prompts, the warnings did not change the production process of the students much. It has been seen that they usually search for new images by making arrangements in the first prompts they wrote.

In addition, there were various errors in AI tools when the studio was built. Illogical space-building-human could appear in the images produced. Some students thought that AI-induced mistakes were caused by their prompts and tried to fix them themselves. Although they could create the idea in their minds, they gave up due to technical errors and produced new alternatives. Moreover, the artificial intelligence tools used were either free or a free version of a paid AI tool. Free AI tools bring with them various limitations. Producing a limited number of alternatives in a day, the low resolution of the created image, or producing a free user image last if there are different images in the queue are various examples of these restrictions. Free version restrictions prevented students from making more alternatives and caused them not to have a close relationship with AI tools.

Finally, we see that AI and its effects are inevitable in design education, and this study contributes to comprehending the role of AI in first-year students' design processes. Hence, by examining the role of AI in the design process, new syllabi and curricula can be improved by integrating AI. In this study, we preferred to include AI in the last phase to prevent tendencies to leave the majority of the design process to AI without sufficient experience. However, with experience, AI can be utilized as a co-designer in the process by applying different methodologies.

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COMPARING DESIGN PRODUCTIVITY BETWEEN PHYSICAL AND VIRTUAL REALITY MODELING

Protocol analysis for the early design stages

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Abstract. Investigating productivity in the design process by comparing physical and virtual reality modeling constitutes the problem defined by the study, since both mediums grant the interaction between the body and design object. The study, it is aimed to decode the productivity of the early design stages. The study uses the Linkography method and protocol analysis with the think-aloud method for the quantitative measurement and analysis of productivity. In the protocol analysis, the participants, all of them architects, were expected to propose a solution for the architectural design problem, first with a physical model and then with a virtual reality environment, three days apart. The results of the study show that the productivity results in the physical model are higher than the results in the virtual reality modeling. The differences suggest that the medium used in the design processes has a direct impact on the design process and productivity.

Keywords: *Cognition, Design Productivity, Physical Model, Virtual Reality, Linkography.*

ملخص. تكمن مشكلة البحث فى التحقيق في مسألة الإنتاجية في عملية التصميم من خلال مقارنة نمذجة الواقع المادي والافتراضي، حيث أن كلا الوسيطين يمنحان التفاعل بين الجسم وكائن التصميم. وتهدف الدراسة إلى فك رموز إنتاجية مراحل التصميم المبكرة. تستخدم الدراسة منهجية اللينكوجرافى وتحليل البروتوكول مع طريقة التفكير بصوت عال للقياس الكمي وتحليل الإنتاجية. في تحليل البروتوكول، كان من المتوقع من المشاركين، وجميعهم معماريون، أن يقترحوا حلاً لمشكلة معمارية، أولاً بنموذج مادي ثم باستخدام بيئة الواقع الافتراضي، بفارق ثلاثة أيام. وأظهرت نتائج الدراسة أن النتائج الإنتاجية في النموذج المادي أعلى من النتائج في نمذجة الواقع الافتراضي. وتشير الاختلافات إلى أن الوسيلة المستخدمة في عمليات التصميم لها تأثير مباشر على عملية التصميم والإنتاجية.

الكلمات المفتاحية: *المعرفة، الإنتاجية فى التصميم، النماذج المادية، الواقع الافتراضى، منهجية اللينكوجرافى.*

1. Introduction

Cognition in design provides information about the process within design and tries to understand how design thinking occurs. The importance of cognition in design depends on the designers' understanding of how they express or act on a particular design problem and the appropriate measurement techniques. One of the basic constructs in the field of cognition in design, put forward by Schön (1987), is that the design has a reflective process rather than a linear process. According to Schön, when designers sketch something instead of just thinking about it, they can generate more information about previous design moves in the design process to record the ‘inner thought’ and reduce their mental load. Using an external memory tool, allows the designer to switch between design steps. The use of an external tool is not restricted to mere recording of thought. There are also various ways of recording thought using different representational tools. However, each external tool offers different possibilities to the designer, so it is the process of the design process depending on the different representation media. For example, the study of Salman *et al*. (2014) observed that the use of CAD software by participants changes the process of design. It has been observed that students who use CAD software during the design process pass from an idea more slowly than a motion sketch, spend less time analyzing the design problem, and focus on details, which consumes most of their time.

Throughout the design process, the designer shifts between various mediums and scales. The situation seen in Dorta *et al*.'s study (2016) also shows the change in the design environment that the designer uses to reveal his thinking. In the 9-week study, the participants used 2D and 3D sketches intensively in the early stages of the design to convey and shape their ideas, and after the 5th week, the sketches were replaced by digital modeling. In the last weeks, physical models and animations have been used. This study shows us that the design activity takes place in the representational medium that best suits the design question at hand.

Although we observe that virtual reality, which has recently started to be integrated into the design world, also contributes to the designer in terms of representing three-dimensional thinking and shapes the thought, studies examining virtual reality and the design process are in the minority in the literature. For example, it has been investigated how the use of physical models and the use of virtual reality affect creativity in the design process. While it has been observed that the use of physical models increases creativity in the early stages of design, it has been observed that virtual reality supports creativity in the later stages of design (Sachanowicz, 2019; Abdelhameed, 2017). However, the comparison of productivity instead of creativity in design is not studied deeply, and the study aims to fulfill this deficiency in literature.

Moreover, the aim of the study is to investigate the use of innovative, technological medium in the design process, and to compare them with the physical models, which are seen as traditional design mediums, based on their productivity in the design process. The motivation behind this study is to investigate different mediums that can grant the chance to interact between the designer's body and design object. The study predicts that the productivity values in the design processes in two different design environments are close to each other. However, the study expects that the forelinks/backlinks ratio will be at a higher rate in the VR environment than physical model since the designer can easily shifts between different scales. Figure 1 shows the research frame of the study.

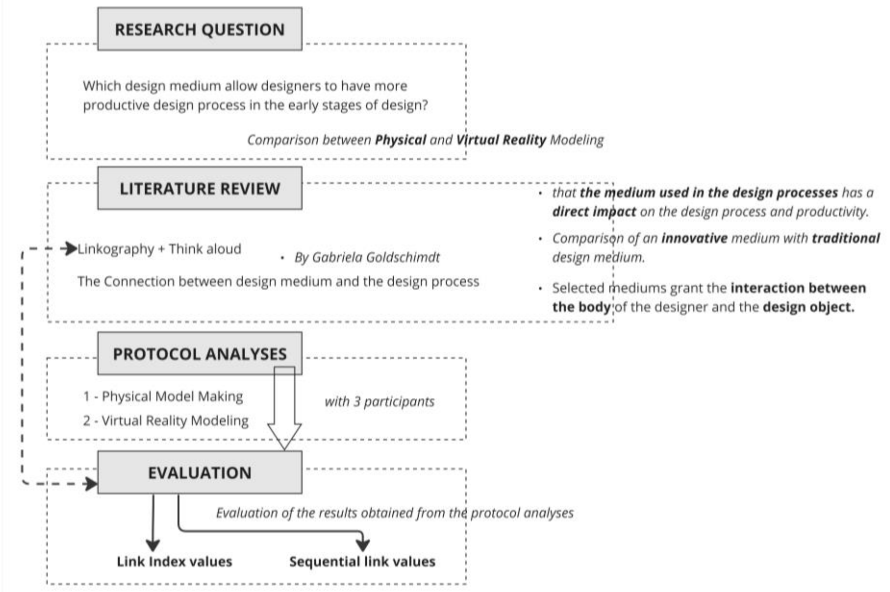

Figure 1. Research frame of the study.

The study compared the design process through physical and virtual reality modeling, when trying to reduce the effect of the variable depending on the designer and the defined architectural design problem. Because the study was based on comparing design processes in different representational mediums, two different protocol analyses were conducted with the same participants, first with a physical model and then with a virtual reality environment. The data obtained from the protocol analysis were coded by the Linkography method introduced to the literature by Goldschmidt (1990).

In the next section, information about the method is given. After the method, the protocol analysis is presented. After the explanation of the protocol analysis, the Linkography method was explained, and the analysis of the studies was carried out. Later, the analyses, the evaluation and discussion section, and finally, the conclusion section are included.

2. Method

It is seen that protocol analysis is mostly used as a method in studies in the field of cognition in design. Protocol analysis are considered to be directly accessible to the designer's cognitive processes, unlike other empirical study methods (Hay *et.al*., 2017). There are also various sub-methods in protocol analysis. The most widely used is the think-aloud method (Ericsson & Simon, 1993). In the thinking-aloud method, the participant's actions and thoughts during the design process should be verbally expressed, and their actions should be recorded. After the recorded statements and actions are examined, necessary analyses are carried out.

In the literature, one of the points criticized in the thinking aloud method is that it is thought to affect the designer's perception in the process (Suwa & Tversky, 1997). In contrast, according to Ericson and Simon, the pre-made think-aloud exercises revealed that thinking-aloud did not cause major changes on the process (Ericson and Simon, 1993, quoted in Özbaki, 2016a). In order to minimize the risk of affecting the perception of the designers, they are exercised before the protocol analysis.

In the literature, the design processes carried out in various design mediums have been compared with the Linkograf method on productivity. While a comparison was made between the physical model and digital modeling in Özbaki's study (2016b), a triple comparison of the sketch, physical model, and digital modeling was made in Gürsoy's MA dissertation (2010). In the studies, they defined the design problems to the designer and asked them to solve these problems through various mediums. For example, the program of the design problem given in both studies and the location selection have similar features. In this way, they investigated the effects of the design medium by reducing the effect of the variable depending on the designer and the defined architectural design problem. In both studies, protocol analysis was performed, and the thinking-aloud method was preferred. The data obtained from the protocol analysis were analyzed by the Linkography method.

As a result, in the study, similar to the studies in the literature, it was found appropriate to use the think-aloud method in protocol analysis. In addition, it was found appropriate to use the Linkography method in the study. It is, therefore important to observe the design process as clearly as possible. In this way, it is easier to detect links and design moves in the design process compared to other sub-methods. Elaboration on the Linkography method will be made in Chapter 4.

3. Protocol Analysis

In the protocol analysis, the study was carried out in two different representation mediums, and the designer was expected to find a solution to the determined design problem first with the physical model making and then to develop the other defined design problem using virtual reality, three days apart. While designing problems, well-defined problem definitions were given rather than ill-defined problems defined by Simon (1973). The reason for this is to try to minimize the variation of the design process that will emerge according to the background knowledge of the designers. Defining the problem definitions as close to each other for both design problems can be explained as reducing the variability of the design problem and highlighting the effect of the representational environment in which the design takes place. Another important element while creating the architectural design is the environmental data related to the land. In both problem definitions, elements such as similar topography, sizes, and relationship with surrounding buildings and main roads have been tried to be defined similarly. When defining both design problems, it is important that they are not identical but differ with minor changes because the participants' thoughts in the first design problem should not reflect the process in the second design problem. In the protocol analysis, productivity in the design process was tried to be measured through the conceptual design process, the early stages of design. All three participants are architects and Ph.D. students. While determining the participant profile, the aim of choosing the participants' physical and digital modeling levels to be close to each other was practical.

3.1. DESIGN STUDY WITH A PHYSICAL MODEL (PM)

In the physical model (PM) study, the participants worked on the physical model, and their actions were recorded in order to be able to analyze it later. For this, a camera was placed in the work area where the physical model was made. In addition, since the think-aloud method was applied, a sound recording was also taken as well as the video recording.

For the implementation of PM, a 1/500 scale model was studied. The reason for using a 1/500 scale model is that it is considered an appropriate scale for architectural expression techniques to work in early design stages.

For the physical model study, a physical model including surrounding buildings, roads, and contour lines was given to the participant. In order to make their own model, a foam core with a thickness of 2 millimeters, scissors, a utility knife, glue, office pins and a ruler was provided. Figure 2 shows the Physical Model working environment.

Figure 2. Physical model study environment.

The land chosen for the physical model is in Sancaktepe, Istanbul. The design problem is housing units. It was requested that the housing units be differentiated according to their various usage needs and sizes, and when creating the program, the participant is expected to create 4 * 3+1 flat types, 6 * 2+1 flat types, and 4 * 1+1 flat types. In addition to this, it includes a design problem that can serve the residences jointly but does not allow outside users and is expected to serve 30 people. Figure 2 shows the design scenario for the physical model. A printout of the image in Figure 3 was given to the participant.

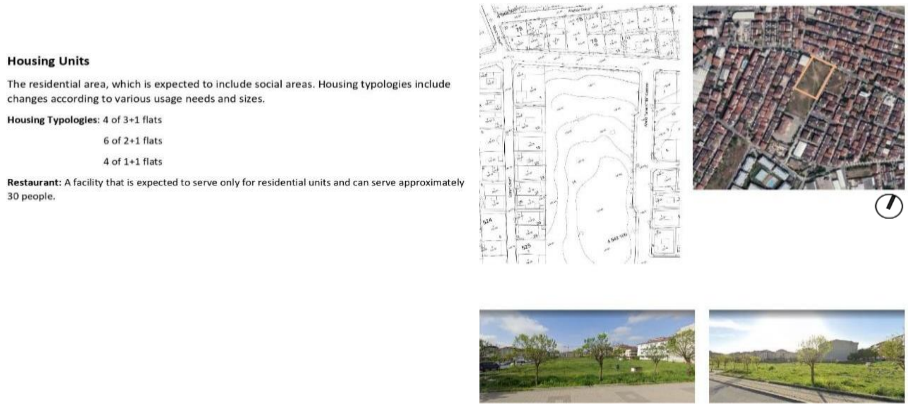

Figure 3. Design scenario for physical model study.

There was no time limit for the participant to perform the physical model work. The design process ended when the participants found the design product they developed "satisfactory." Participant X's study took 22 minutes. Participant Y's study took 41, and participant Z's study took 51 minutes.

3.2. DESIGN STUDY THROUGH VIRTUAL REALITY (VR)

In the second design study developed using virtual reality (VR), the participants worked in a virtual reality environment. The participants' actions in the virtual reality environment were recorded via screen recording, and their voices were recorded since the think-aloud method will be applied to analyze them later.

Since VR was performed through virtual reality, virtual reality headsets were given to the participants. Before the study, the participant was given training in order to experience working in the VR environment and to have foreknowledge about the tool. The training lasts 150 minutes on average. The VR Sketch program developed by SketchUp was used in the study carried out for virtual reality modeling. The reason for choosing this program is that it has an interface similar to SketchUp, the commands are similar, and it is easy to work on architectural design since all of the participants are familiar with the SketchUp interface. Oculus Quest 2 was used as a virtual reality device (Figure 4).

Figure 4. Virtual reality study environment with Oculus Quest 2.

The model given in the virtual reality environment has the same land boundary size as the physical model and includes the same type of environmental data like buildings, roads, and contour lines. Figure 5 shows the base 3D model for the VR study.

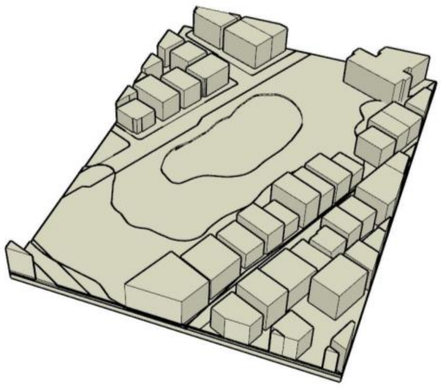

Figure 5. A 3D model was provided to the participants for the virtual reality study.

The area selected for virtual reality is in Sancaktepe, Istanbul. The design problem is the dormitory building for secondary school students. The room types in the dormitory building are classified as 4-person, 2-person, and 1-person. The participant is expected to create 4 dormitory rooms for 4 people, 6 rooms for 2 people and 4 rooms for 1 person (for 32 people). In addition to this, a design problem has been defined with a cafe that can serve to the dormitory building and is expected to be open to customers from outside and is expected to serve around 30 people. A printout of the image in Figure 6 shows the design scenario for virtual reality modeling given to the participant.

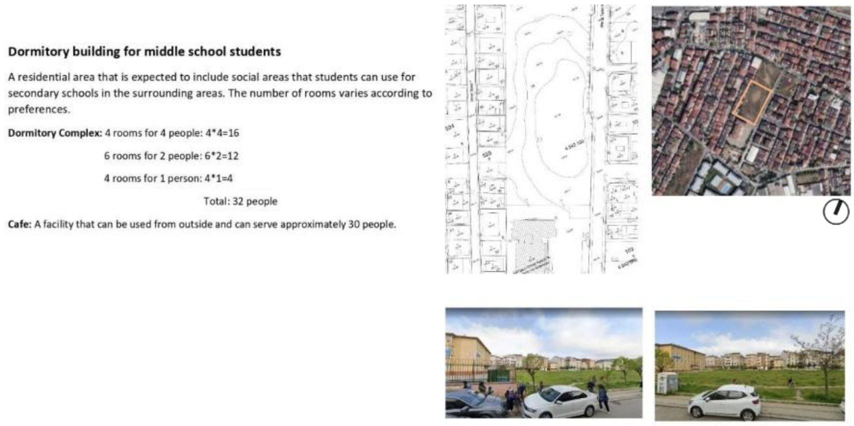

Figure 6. Design scenario for virtual reality study.

There was no time limit for the participant to perform the virtual reality modeling. The design process ended when the participants found the design product they developed "satisfactory”. Participant X's study took 73 minutes. The participant Y's study took 58, and the participant Z’s study took 108 minutes.

4. Linkography Analysis

Goldschmidt, G. (1990) introduced the Linkography method in her research on cognition and productivity in design and refers to the study of the connections and relationships between different design moves in the design process. According to Goldschmidt (1990), these connections can be used to measure design productivity as they allow designers to access and use relevant information and resources efficiently. Goldschmidt's work has had a significant impact on the field of design cognition as it helps to shed light on the cognitive processes underlying design productivity.

The Linkography method is a marking and analysis system that focuses on design moves in design processes and the links between these moves (Goldschmidt & Tatsa, 2005). The network structure emerges through the detection and visualization of design movements and connections in the design process. From a standpoint at this point, the design moves and connections need to be defined carefully for this study.

The term design moves refer to certain actions or decisions that designers make during the design process. In the light of the data collected by protocol analysis and thinking aloud method, the designer's thought and action patterns are divided into sub-parts. Each of these sub-parts can be defined as a design movement. These design movements can be related to each other in the design process, or they can be discrete. The study of relationships between design moves is associated with the term link(s). Links are determined by the fact that the two design moves share a certain partnership. Links are determined by whether the content of the two design movements has enough commonality to qualify that common ground as a link. Connections are divided into two. The first of these are backlinks, which depend on previous actions or thoughts. The other one is called forelinks and forms the basis of future moves and thoughts (Goldschmidt & Tatsa, 2005).

For design productivity, The number of design moves, connections and critical moves is important. According to Goldschmidt (1990), the Link index is used to measure the productivity of design and critical moves. Link index is the value obtained by dividing the number of links determined in the Linkography analysis by the number of design movements. A high value indicates that connections are made proportionally more frequently during the design process. Therefore, the Linkography graph will have a much more intricate network and will show that the design process is more productive.

5. Evaluation and discussion

In the study, design moves, links, Link Index, forelinks, and backlinks will be examined in order to establish the productivity in the design process realized through physical models and virtual reality. Goldschmidt states that a higher link index value in Linkography means that the connections between the moves and, therefore, the productivity are high. (Goldschmidt, 1990, quoted in Özbaki, 2016a).

In the protocol analysis, for the participant X, a total of 13 design movements were detected during the design process in PM. Figure 7 shows the Linkography graphic created by the physical model process. There are 18 links between design moves. Therefore, it is seen that the Link index is 19/13, i.e, 1.38. Of the links, 3 are forelinks and 15 are backlinks.

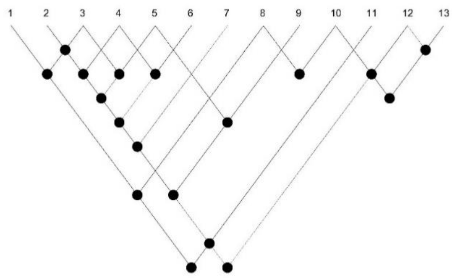

Figure 7. Linkography graph created by physical model study of participant X.

For participant Y, a total of 20 design movements were detected during the design process in PM. Figure 8 shows the Linkography graphic created by the physical model process. There are 32 links between design moves. Therefore, it is seen that the Link index is 32/20, i.e 1.6. Of the links, 11 are forelinks and 21 are backlinks.

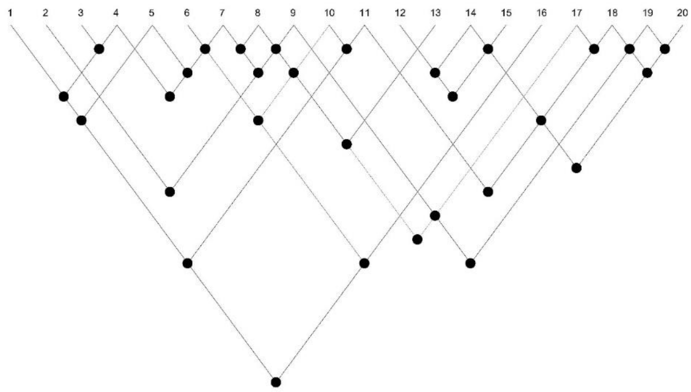

Figure 8. Linkography graph created by physical model study of the participant Y.

For participant Z, a total of 18 design movements were detected during the design process in PM. Figure 9 shows the Linkography graphic created by the physical model process. There are 32 links between design moves. Therefore, it is seen that the Link index is 32/18, i.e 1.77. Of the links, 4 are forelinks and 28 are backlinks.

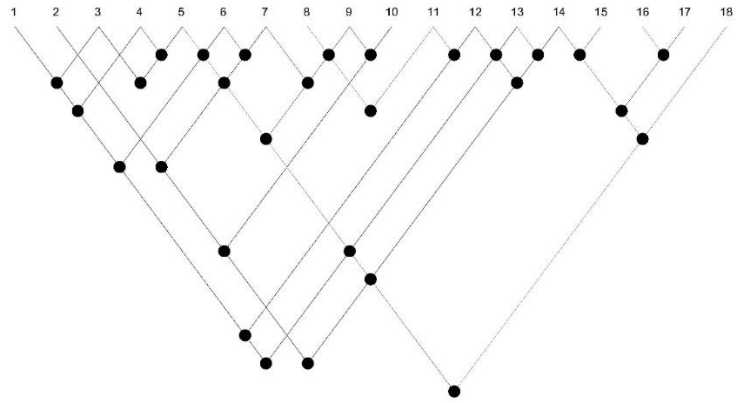

Figure 9. Linkography graph created by physical model study of the participant Z.

When looking at the design process in the VR of the participant X, a total of 19 design movements were identified. Figure 10 shows the Linkography graph created by the virtual reality process. There are 18 links between design movements. Therefore, it is seen that the Link index is 18/19, that is, 0.94. 4 of the links are forelinks, 14 are backlinks.

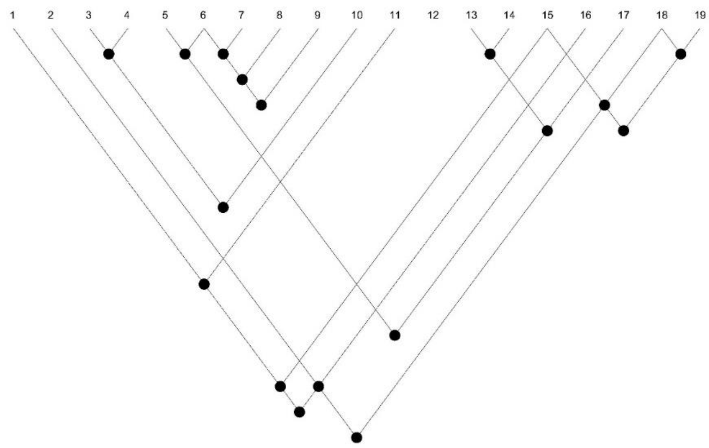

Figure 10. Linkography graph created by virtual reality study of the participant X.

For the participant Y, a total of 17 design movements were detected during the design process in VR. There are 29 links between design moves. Therefore, it is seen that the Link index is 29/17, i.e 1.70. Of the links, 6 are forelinks and 23 are backlinks. Figure 11 shows the Linkography graphic of the participant Y.

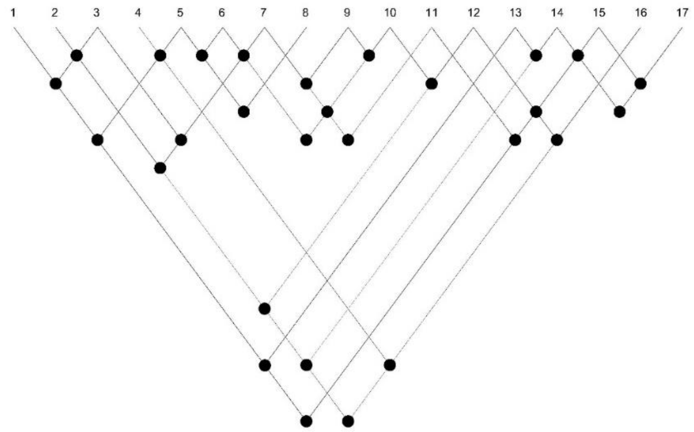

Figure 11. Linkography graph created by virtual reality study of the participant Y.

For the participant Z, a total of 19 design movements were detected during the design process in VR. There are 29 links between design moves. Figure 12 shows the Linkography graphic of VR results of Participant Z. The Link index is 29/19, i.e 1.52. Of the links, 7 are forelinks, and 22 are backlinks.

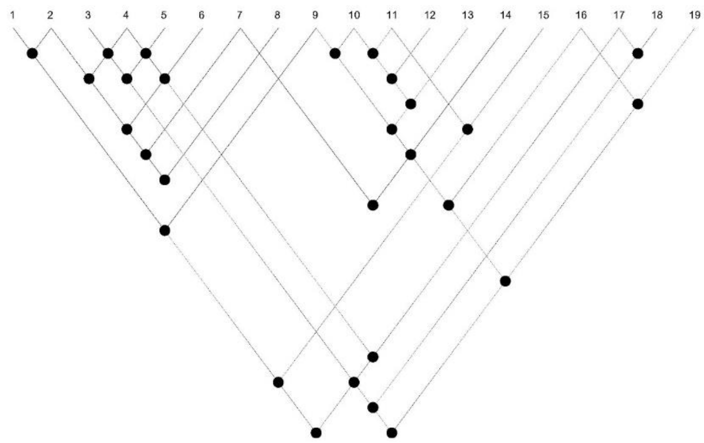

Figure 12. Linkography graph created by virtual reality study of participant Z.

When the link indexes obtained from two different representation mediums are compared, it is seen that, at least for the two participants, the result in the PM is higher than the result in the VR. These values are close to each other, but it can still be said that design development with physical model-making gives more productive process.

Looking at the Linkography graphics, it is observed that physical model study involves more connections that trigger each other sequentially. In total, it is observed that 18 single-hop connections (connecting with the move immediately after or before it), 9 double-hop, and 8 three-hop connections are established in VR work; it has been observed that 21 single-hop connections, 16 two-hop connections, and 8 three-hop connections are established in PM (Table 1). Since these results may indicate that, while developing a design with model making, designers deal with a problem until they solve or satisfied with it. That makes the sequential connections more frequent than in VR. Even though participant Y has a higher link index in VR, the participant has more sequential connections in physical model-making. Comparing two different design mediums, physical model-making generates a more productive design process because of sequential connections.

The ratios of backlinks and forelinks to each other in the design processes developed in physical models and virtual reality environments were examined. The purpose of this calculation is whether the reflexive process inherent in the design has changed in various mediums. Therefore, the ratio of forelinks to backlinks can tell us how integrated the designer has handled the process. When the physical model process is examined, it is seen that 21 of 83 links, which means 21/83=0.25, in total are forelinks. When the design developed over virtual reality is examined, it is seen that there are 17 forelinks out of 76 links in total, which means 17/76=0.22. As a result, contrary to the expectations of the study, no significant difference was found between the two mediums regarding the formation of forelinks and backlinks.

TABLE 1. Sequential Connections on different participants and their ratio of sequential links in total links.

Physical Model

	single-hop	double-hop	triple-hop	ratio of sequential links and total links
Participant X	2	6	2	10/18=0.55
Participant Y	9	5	3	17/32=0.53
Participant Z	10	5	3	18/32=0.56
			Avarage in total	**45/82=0.55**

Virtual Reality

	single-hop	double-hop	triple-hop	ratio of sequential links and total links
Participant X	5	1	2	8/18=0.44
Participant Y	7	4	4	15/29=0.51
Participant Z	6	4	2	12/29=0.41
			Avarage in total	**35/76=0.46**

The ratios of backlinks and forelinks to each other in the design processes developed in physical models and virtual reality environments were examined. The purpose of this calculation is to determine whether the reflexive process inherent in the design has changed in various mediums. Therefore, the ratio of forelinks to backlinks can tell us how integrated the designer has handled the process. When the physical model process is examined, it is seen that 21 of 83 links, which means 21/83=0.25, in total, are forelinks. When the design developed over virtual reality is examined, it is seen that there are 17 forelinks out of 76 links in total, which means 17/76=0.22. As a result, contrary to the expectations of the study, no significant difference was found between the two mediums regarding the formation of forelinks and backlinks.

On the other hand, the fact that the production with a physical model is more productive for the design process should not cause us to realize some of the potential of VR. For example, Figure 13 shows a screenshot from the study, the participant X notices the yellow mass (dormitory) is too close to the white mass (café) when the participant sees the formation from first person view and arranges their location afterward. Therefore, instead of using only a specific design medium during the design process, using both design mediums according to the needs of the problem at hand can be beneficial for the design process and contribute to the reflexive process which is inherent in the design.

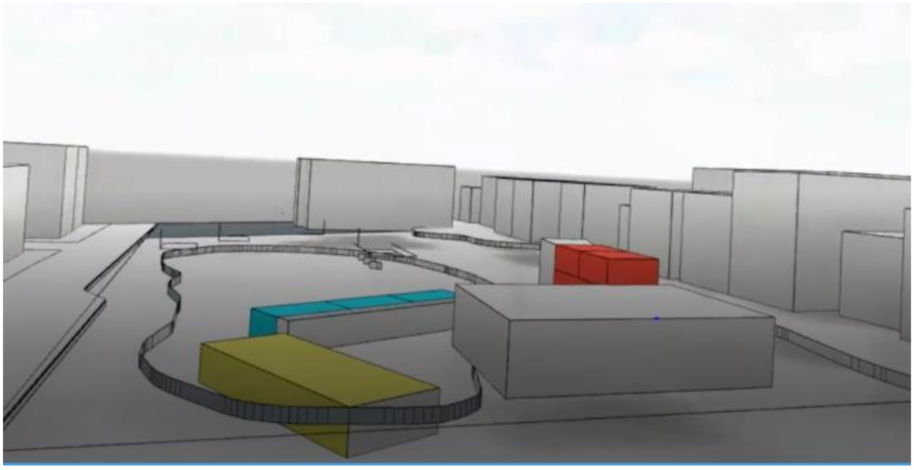

Figure 13. A screenshot from the VRSketch interface in the study.

6. Conclusion

Investigating productivity in the design process by comparing it with the physical model making and virtual reality model making constitutes the problem defined by the study, since both mediums grant the interaction between the body of the designer and the design object. The study observes that design development with physical model gives a higher productivity value than design development with virtual reality. It has been determined that the Link Index in the design process with a physical model is 1.58 on average, while the Link Index in the design process using virtual reality is 1.38 in average. Table 2 shows the participants' Link Index in different mediums and their average Link Index values. Considering the values of Link Indexes and sequential connections, the main difference that causes productivity differences between these two mediums originates from the frequency of sequential connections.

TABLE 2. Link Index values of different participants and their average values.

Link Index

	Physical Model (PM)	Virtual Reality (VR)
Participant X	1.38	0.94
Participant Y	1.60	1.70
Participant Z	1.77	1.52
Avarage	**1.58**	**1.38**

Looking at the Linkography graphics, it is observed that the physical model involves more connections that trigger each other sequentially. When the work of the participants was observed, it was observed that the reason for this was that the participant's movements concentrated on a similar problem until they found a solution to the design problem they were dealing with while working with a physical model. However, it was observed that the participants, who were able to switch between different scales while working in the VR environment, did not stay on a specific problem but made transitions to different design problems and stages. According to the results obtained from the study, designs developed in two different mediums have differences in terms of productivity as well as providing different approaches to the designer. As a result, the medium used in the design processes has a direct impact on the design process and productivity.

There are some overlaps and divergences between the results obtained with the hypothesis of the study. The data obtained in the study, which predicts that the productivity values in the design processes taking place in two different design mediums are close to each other, show that design development with a physical model gives a slightly more productive process than development with virtual reality. However, the hypothesis of the study, which predicts that forelinks in total link ratio will be at a higher rate in the VR environment than in the physical model, contradicts the results obtained since there is not any correspondence observed with the forelinks and backlinks with the design medium.

However, the study still contains some deficiencies. By expanding the scope of the study, working through the whole process of design rather than the early stages of design, it may be more efficient to compare the productivity realized in two different design mediums. In addition, the number of participants may be increased. In that way, it would be easier to generalize the findings. Finally, patterns that are developed by Goldschmidt, such as Chunk, Web, and Sawtooth Track, can be used to establish productivity in the study. In this way, more methods can be used to analyze productivity.

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USER EXPERIENCE AND INTERACTION DESIGN IN ARCHITECTURE'S NEW MEDIA

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Abstract. As immersive technologies, notably Virtual Reality (VR), gain traction in the Architecture, Engineering, and Construction (AEC) sectors, there is an increasing emphasis on their application in education and industry. This article delves into the use of VR in these spatial disciplines and underscores the limited attention given to the User Experience and Interaction Design. The authors have developed and evaluated a VR interaction approach, comparing two methods: direct and indirect interaction. Direct interaction offers a real-world, intuitive approach, where users physically interact with virtual objects. In contrast, indirect interaction uses an intermediary interface for more precision in control, albeit with a slower response time. Utilizing an immersive framework for UX, the study aims to understand which method offers better user experience. Through an experiment the authors revealed that users with a design background found it easier to use the interface and interact within the VR setting. Interestingly, while direct interaction was initially thought to be more efficient, the indirect method's precision offered distinct advantages in specific design stages. This research accentuates the potential of tailored VR interaction methods depending on the design process stage and user background.

Keywords: *Virtual Reality, User Experience, Interaction Design, Human-Computer Interaction*

ملخص. مع اكتساب التقنيات الغامرة، ولا سيما الواقع الافتراضي (VR)، قوة جذب في قطاعات الهندسة المعمارية والهندسة والبناء (AEC)، هناك تركيز متزايد على تطبيقها في التعليم والصناعة. تتعمق هذه المقالة في استخدام الواقع الافتراضي في هذه التخصصات المكانية وتؤكد على الاهتمام المحدود الممنوح لتجربة المستخدم وتصميم التفاعل. قام المؤلفون بتطوير وتقييم نهج تفاعل الواقع الافتراضي، بمقارنة طريقتين: التفاعل المباشر وغير المباشر. يوفر التفاعل المباشر أسلوبًا بديهيًا واقعيًا، حيث يتفاعل المستخدمون فعليًا مع الكائنات الافتراضية. في المقابل، يستخدم التفاعل غير المباشر واجهة وسيطة لمزيد من الدقة في التحكم، وإن كان مع زمن استجابة أبطأ. باستخدام إطار عمل غامر لتجربة المستخدم، تهدف الدراسة إلى فهم الطريقة التي توفر تجربة أفضل للمستخدم. من خلال التجربة، كشف المؤلفون أن المستخدمين ذوي الخلفية التصميمية وجدوا أنه من الأسهل استخدام الواجهة والتفاعل داخل إعداد الواقع الافتراضي. ومن المثير للاهتمام، أنه في حين كان يُعتقد في البداية أن التفاعل المباشر أكثر كفاءة، فإن دقة الطريقة غير المباشرة قدمت مزايا مميزة في مراحل تصميم محددة. يبرز هذا البحث إمكانات أساليب تفاعل الواقع الافتراضي المخصصة اعتمادًا على مرحلة عملية التصميم وخلفية المستخدم.

الكلمات المفتاحية: *الواقع الافتراضى، تجربة المستخدم، تصميم التفاعل، التفاعل بين الإنسان والآلة.*

1. Introduction

Immersive technologies, such as Virtual Reality (VR) is becoming increasingly affordable, which has led to its growing use in the Architecture, Engineering, and Construction (AEC) education and industry. AEC fields, along with other spatial disciplines such as geography and geology are increasingly tapping into immersive technology, drawn by its numerous advantages in virtual environments. These include minimizing distractions, offering varied perspectives, and fostering engagement through hands-on activities (Oprean and Balakrishnan, 2020). Consequently, researchers in these areas have spent a substantial attention to the uses cases of VR systems, practical implication of using different VR tools, and have proposed many efficient and optimized methods of implementing in terms of both hardware and software. To this end, less attention has been given to the User Experience (UX), User Interface (UI) and Interaction Design (IxD).

In this article, the authors explore the role of Human-Computer Interaction (HCI) theories in the design and development of a VR interaction approach, which they developed and tested. This study compares two interaction methods, namely *direct* and *indirect interaction*, in terms of their usability and effectiveness. In the *direct interaction* method, users can select any object within the virtual environment (VE) by pointing the controllers at the object, opening the menu, and selecting a command such as move or rotate. The selected command will then automatically execute, and users can move or rotate the object by moving their hands towards the desired direction. In the *indirect* method, users interact with an interface that provides options to control the object through commands such as directional arrows (up, down, left, and right buttons) in the case of move command. It is through this interface that the object will be moved towards the desired directions.

The immersive framework for UX (Oprean and Balakrishnan, 2020) served as the basis for designing the two interaction methods. This framework emphasizes the importance of UX aspects of immersive technology and how they can enhance spatial understanding and learning. The psychological outcomes of spatial presence, virtual embodiment, and novelty are the main drivers for better understanding and engagement, according to this framework.

2. Background

Immersion can be referred to as both physical and mental degrees to which VR users feel immersed (Emma-Ogbangwo, Cope, Behringer, and Fabri, 2014). The physical aspect relates to the users' sensory engagement (Biocca and Delaney, 1995) and the psychological aspect relates to the user's emotional response– namely involvement, attention, and affection- to the displayed content (Ermi and Mäyrä, 2005). The discourse on immersive technology, specifically in education is split into two: one concentrates on learning effectiveness, while the other delves into the user experience (UX) from a human-computer interaction (HCI) standpoint. But most importantly both emphasize engagement with technology. The UX framework proposed by Oprean and Balakrishnan (2020), address multiple concepts that are critical in user experience. Below, the authors have discussed some of the key concepts that were utilized in the development of their work.

2.1. ENGAGEMENT

Engagement is crucial to the learning process, especially in active learning (Chi and Wylie, 2014). Despite its importance, engagement is a multifaceted term with diverse interpretations (Glas and Pelachaud, 2015). It is frequently equated with concepts such as motivation (Martin, 2012), interest, involvement, immersion, and user experience (Lehmann et al., 2012). Although these terms are interconnected, they each hold distinct meanings. Oprean and Balakrishnan (2020), use the term 'learner engagement' instead of engagement – in order to distinguish the nuances. Learner engagement is a consequence of joyful experience that is supported by novelty of the experience – along with involvement.

2.2. PRESENCE

The idea of "presence" or the sensation of "being there" in a virtual environment is fundamental to User Experience (UX) within immersive technology. In disciplines concerning space, this sensation is often more specifically described as "being within a space", termed as *spatial presence*. Presence is considered a multi-dimensional concept comprising different subjective and interrelated factors (Kalawsky, 1999). According to Lee (2004), different classifications of factors influencing presence have been attempted, such as technology-based and user-based (Slate and Usoh, 1993). IJsselsteijn et al. (2000) suggest four broad groups of variables that affect presence: the extent and fidelity of sensory information, the match between sensors and the display, content factors, and user characteristics.

Research in immersive technology suggest that presence has a pivotal role in understanding and perceiving the virtual environment. Spatial elements in presence help anchor references between objects and content, mirroring the real-world scenarios where navigation, scale, distance, and structure shape how users interpret and recall events (oprean and balakrishnan, 2020). For instance, navigating a new environment often involves drawing upon familiar navigation skills and adjusting based on new experiences. From a UX standpoint, presence fluctuates in intensity throughout an experience, hinting at its reliance on other UX aspects to prolong the immersion. Hence, maintaining ongoing engagement is crucial, necessitating the introduction of varied elements.

2.3. EMBODIMENT

Embodiment, or virtual embodiment, allows users to relate to an environment using their own physical form as a point of reference for engaging in activities (Kilteni et al., 2012). This is different from the sensation where a user feels the actions of an avatar as their own (Dede, 2009). True embodiment is felt when users can interact with a virtual space as naturally as they would with their physical body (Oprean and Balakrishnan, 2020). With advancements in VR technology, users' physical movements are now mapped on their virtual avatar, amplifying the feeling of embodiment. This allows users to navigate the virtual environment, stand at their actual height, and turn their heads for a more realistic perspective. The concept of virtual embodiment was crucial in conceptualization of the design of interaction utilized in this study. For that reason, the authors discuss this concept in more depth.

2.3.1. Sense of Virtual Embodiment

Virtual embodiment, in the context of media technology, is linked to the user's graphic representation within the virtual environment. According to Blanke and Metzinger (2009), having and using a 'body' is a necessary condition in the embodiment. De Vignemont (2011) believes embodiment happens only if a part of the body representation "are processed in the same way as the properties of one's body" (p. 84). Kilteni and her colleagues (2012) proposed a new definition based on de Vignemont's (2011) definition. They introduced the idea of a 'sense of embodiment' as the sensations that one would feel when a user 1) has a body, 2) is inside the body, and 3) has control over the body in the context of VR technology. The difference between the two definitions lies between the part of a body versus the body as a whole. In Kilteni's definition, 'being inside' was operationalized as the *sense of self-location*; 'having a body' addresses the *sense of body-ownership*, and 'controlling a body' refers to the *sense of agency*.

Sense of self-location refers to the feeling inside a spatial volume, which is determined by a vision given an egocentric view, vestibular signals, and tactile inputs (Kilteni et al., 2012). *Sense of body-ownersh*ip refers to the feeling of self-attribution towards a body, which can be possessive (Kilteni et al., 2012). Sensorimotor systems, visual, and tactile inputs play a critical role in forming a sense of body-ownership (Gallagher, 2005). *Sense of agency* (SOA) has been defined as the sensation that makes someone feel they are the one generating or causing an action (Gallagher, 2000). SOA is active only when the sensorimotor system is active (Kilteni et al., 2012). Murray (2017) believes that actions with a high degree of agency have three characteristics. First, it must be highly autonomous; second, it must be selected from an extensive range of possibilities of actions; and finally, it must be able to control the course of experience, such as when one plays a chess game. During a VR experience, users can gain SOA by interacting with a mediated environment and its objects. Therefore, interaction design in VR applications play a significant role in forming a sense of virtual embodiment.

2.3.2. Interaction as Agency

Researchers refer to interactivity as how and to what degree users interact with a VR system, and it has been studied as a function of active user participation in VE (Bucy and Tao, 2007). The operationalization of interactivity varies widely. The operationalizations have been as diverse as the level of involvement (Cowan and Ketron, 2019) and navigability (Oprean, 2014). In current work, the authors consider interaction as a function of technology affordance that pertains to the user's SOA. In the real world, individuals naturally engage with their surroundings without consciously considering the connection between their actions and the resulting consequences. They gauge the anticipated visual response from their motor actions against the actual movement they observe. A mismatch or delay in this assessment can diminish or even nullify our sense of agency.

There are different operationalizations of agency that VR researchers have proposed, based on the topic of their study. These operational definitions mostly involve the intentional control of virtual body or body parts that either focuses on the synchrony of bodily movement – e.g. "if I move arm does my virtual arm also moves in the same direction?" – or the accuracy of these movement, such as corresponding finger movements between physical body and the virtual one. However, in the context of human-computer interaction for computer-aided design (CAD) application, it would not be helpful if we operationally define a concept as binary variable that only one of conditions is to our interest. For example, in the case of accuracy of body parts movement as 'sense of agency', the researcher operationalizes a condition as 'accurate' to measure 'sense of agency' and the 'inaccurate' condition is the null condition (Jeunet et al., 2018). However, in the field of CAD, the practical and rational way of operationally define a concept is where both the controlled and null condition provide specific benefits that the other condition lack.

The two methods of interaction designed and implemented for this study were proposed based on the idea of *direct* and *indirect interaction*. By *direct interaction*, the authors refer to the user's interaction with the virtual environment and objects that occur within a minimum time that typically a user to select an object and perform an action, such as moving furniture to rearrange a room. In the indirect interaction, however, there is a mediating interface, through which users can control different objects. While the *direct interaction* is quick and intuitive, it resembles 'real world' interaction – a concept close to 'presence'; whereas, in the *indirect interaction* the users would require more time to execute an action. The benefit of having indirect interaction lied in the accuracy of controlling and executing commands to move, rotate, or control objects in the virtual environment.

3. Implementation of the Interaction Design

To model the virtual environment, authors used 3ds Max and for the implementation of interactions and constraints, Unity Game Engine was utilized. The virtual environment developed for this project included a single-story office space, which was implemented for HTC VIVE Pro 2 head-mounted display. It allowed users to interact with the environment and objects to perform five commands namely, move, scale, copy, rotate, and change of color/material. Therefore, both *direct* and *indirect interaction* conditions. Figure 1 demonstrates how users interact with furniture in the *direct interaction* method.

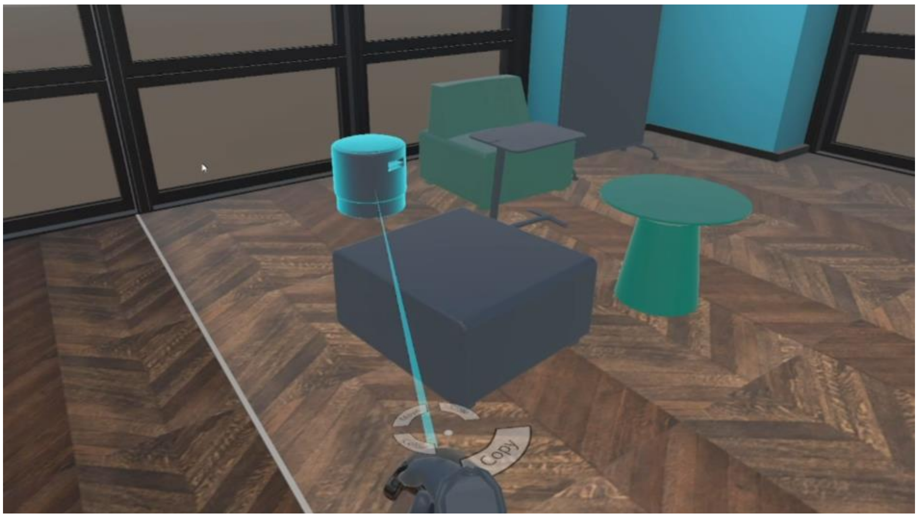

Figure 1. Selecting and copying commands using direct interaction.

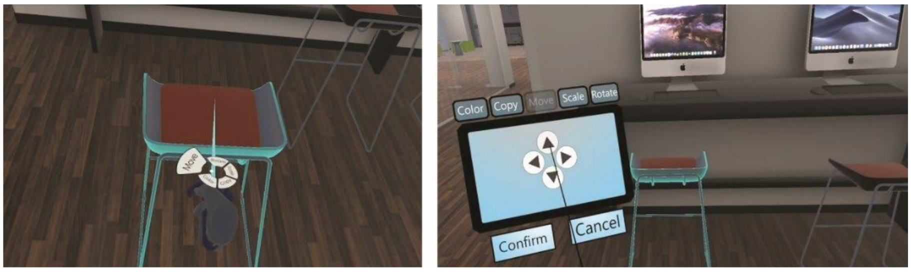

Figure 2. Selecting the object (stool) and choosing the 'move' command (left image) and mediating interface to control and execute the command (right image) in the indirect interaction.

In the *indirect* interaction, the mediating interface allowed users to control and execute the commands as it appears on figure 2. The commands, in this case the 'move' command, executes based on the initial orientation of user's view towards the object. For instance, the 'down arrow' would move the stool towards the direction of the user. Once the command is executed, the user can either 'confirm' it to save the new position, or 'cancel' to reconfigure it to its original position/state. The 'control interface' in the *indirect* method would slowly move with the movement and navigation of the user unless the command is either confirmed or canceled. It is also noteworthy that in the *indirect* condition, each command executes and snaps within a certain value. For example, when using the 'rotate' command, the objects rotate to snap within 15-degrees of their position towards the specified orientation. To rotate an object for 90-degrees, the user would either click the rotate button six times, or they would click and hold the 'rotate' button long enough to have their desired orientation, while the objects stop rotating for a second before it rotates for another 15-degrees.

The *direct* interaction users can immediately observe the results of their work as they intuitively interact with the environment, whereas, in the *indirect* method users' control everything through the mediating interface. The use of mediating interface results in a slower response to what we as humans are accustomed to in the physical world, and therefore, we hypothesized that the *direct* interaction should result in more SOA. Additionally, the *indirect* interaction requires more cognition and conversion between input and output (Jerald, 2016), which should decrease SOA. The benefit that indirect interaction has to offer is based on the design of snap feature which enables users to have better control over the precision of command execution.

4. Research Method

This study utilized a between-subject experiment using two independent variables (IVs), namely *interaction as agency* and *design background*. The *agency* condition included two levels of *direct* and *indirect* interaction as indicated before. Additionally, the *design background* condition also included two levels of ‘architects’ and ‘non-architects’. Due to formal training, professionals from disciplines such as interior design and architecture usually have more significant architectural design experience than those from fields where information about space or environment is not central to their work, such as business administration or information technology.

The study participants (N=32) were recruited from a midwestern university in the United States. More than half of participants (N=19) identified as male, with 13 female subjects. Each study condition received 8 participants, who were either undergraduate or graduate students. Half of study participants majored in architecture or interior architecture, and the other half were from disciplines that are not related to space and/environment, such as journalism, information technology, etc. The researchers randomly assigned participants into the ‘interaction as agency’ conditions to measure two primary outcome variables.

The outcome variables included ‘ease of use’ for the interface and usability for task performance. Measures of usability for both interface and tasks were collected by adopting a 10-item user experience questionnaire on an 8-point Likert-type scale from Lewis and Sauro (2021). These questions assessed user’s experience with ways of interacting and completing tasks using VR.

5. Results

The data was tested for normality and homogeneity of variance-covariance. While ‘ease of use’ for the interface met all the assumption, the usability of ‘task performance’ was not normally distributed; however, its skewness and kurtosis were within an acceptable range of ±2.0.

A two-way ANOVA was conducted to examine the effect of ‘interaction as agency’ and ‘design background’ on measures of ease of use for the interface, as well as usability of ‘task performance’. For the ‘ease of use’ of the interface, there was no significant main effect for 'interaction as agency'. However, there was a significant main effect for *design background* $F(1, 28) = 4.16$, $p < .05$, where participants with *design background* reported a significantly lower score, compared to those with *no design background*. Additionally, the authors found no interaction effect between the IVs.

Authors also found a significant main effect in both *interaction as agency* and *design background* when assessing the usability of 'task performance'. The analysis revealed a significant main effect for *interaction as agency* on 'task performance' $F(1, 28) = 6.86$, $p < .05$, where users in the *indirect interaction* condition reported significantly lower than *direct interaction* condition. Moreover, the results suggest a significant main effect for *design background* on usability of 'task performance' $F(1, 28) = 6.11$, $p < .05$, where users with design background reporting significantly lower score than those without design background. And finally, no interaction effect was found between the IVs for the usability of 'task performance'.

To summarize the results, the authors found that users with design background score lower in both 'ease of use' for the interface and usability of 'task performance', compared to those with no design background – which was an expected result. However, the authors initially believed users in the direct interaction would score lower for both 'ease of use' for the interface and usability of 'task performance'. However, the results suggest the scores between direct and indirect interaction conditions were somewhat similar. Another unexpected result was that users in the indirect interaction condition scored lower in the usability of 'task performance'.

6. Discussion

In this study, the authors implemented an interactive VR scene where users can interact with the environment and its objects using two different methods of *direct* and *indirect* interaction. The conceptualization of these interactions was based on the idea SOA, which can impact sense of presence and result in better engagement.

The analysis of data indicated that users in the indirect interaction condition had easier time to complete the tasks compared to direct interaction. One reason that helps explain this unexpected result could be due to the fact that the indirect interaction method afforded users with higher precision of control over different commands. For example, if a user is creating a cluster of furniture for social interaction and wants the seats to have a certain angle in relation to one another – the indirect condition could provide higher precision of rotation. Direct interaction on the other hand results in a faster response, but since it works as a 'free hand', the results would not necessarily be what the user wants. The difference between direct interaction and indirect interaction could be somewhat compared to the difference between sketching and drafting; they both could be beneficial if they are utilized in the correct stage of design process. Therefore, this result could indicate when implementing a VR scene, the way we design interactions could optimize our workflow given the phase of design process.

If the project is still in the early stages of design, then speed is a priority over precision, and therefore direct interaction could be more efficient. Whereas, if we are implementing a VR environment for a client and the work is in the latter stages of the design process it is rather precision that could help us.

Another result derived from this study suggests that it was easier for individuals with design background, as opposed to non-designers, to use the interface and interact with the VR scene to complete a design task. While the result aligned with our expectations, the details of the test suggest that the observed insignificant effect might change if we recruited more participants for each condition. For professionals integrating VR into their workflow, it might be beneficial to tailor training programs based on participants' background. Those without a design background might need more comprehensive training, while design professionals might need just a quick overview.

While the study provided valuable insights into the varied efficacy of VR interfaces for designers and non-designers, there were certain limitations. The study might not account for variations within the broad categories of "designers" and "non-designers", potentially overlooking the nuances in experience and familiarity with VR or other digital tools within these groups. Moreover, the results may have been influenced by unaccounted variables, such as the specific design tasks chosen, or the particular VR interface used. The sample size and demographic diversity of participants could also have impacted the generalizability of the findings, making them less applicable to broader populations or different cultural or professional contexts.

Future research should delve deeper into the specific competencies and experiences that make VR interactions more intuitive for some individuals over others. Additionally, it would also be valuable to employ a wider range of VR interfaces and design tasks in the study to ensure the results are not skewed by specific toolset features.

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THE ROLE OF TEAM COGNITION IN THE DIGITAL MEDIA FOR ARCHITECTURAL DESIGN TEAMS

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Abstract. This study delves into the intricacies of collaborative design teams, examining how Team Mental Model (TMM) and Transactive Memory System (TMS) correlate with the selection and elimination of ideas during the ideation phase. Utilizing team cognition theories, the research assessed the influence of various media on team decision-making and how the team's verbal interactions pertain to TMM and its relationship with decision-making. Using protocol analysis, the study examined the verbal communication processes that contribute to TMM formation, focusing on the aspects that correlated most with idea selection and rejection. The findings indicate a relationship between discussion duration and idea choice, as well as revisiting and developing ideas. Notably, the results revealed that ideas which received mixed feedback, encompassing both acceptance and rejection, signified team conflict. This research offers valuable insights into the dynamics of team ideation processes, though a more extensive examination of the specific conflicts within teams and a comparison with other studies is advocated.

Keywords: *Team Cognition; Team Mental Model; Transactive Memory System; Collaborative Design*

THE ROLE OF TEAM COGNITION IN THE DIGITAL MEDIA FOR ARCHITECTURAL DESIGN TEAMS

ملخص. تتعمق هذه الدراسة في تعقيدات فرق التصميم التعاونية، وتدرس كيفية ارتباط النموذج العقلي للفريق (TMM) ونظام الذاكرة التفاعلية (TMS) باختيار الأفكار وإزالتها أثناء مرحلة التفكير. باستخدام نظريات الإدراك الجماعي، قام البحث بتقييم تأثير وسائل الإعلام المختلفة على اتخاذ القرار الجماعي وكيفية ارتباط التفاعلات اللفظية للفريق بـ TMM وعلاقتها باتخاذ القرار. وباستخدام تحليل البروتوكول، فحصت الدراسة عمليات الاتصال اللفظي التي تساهم في تكوين TMM، مع التركيز على الجوانب الأكثر ارتباطاً باختيار الفكرة ورفضها. وتشير النتائج إلى وجود علاقة بين مدة المناقشة واختيار الفكرة، وكذلك إعادة النظر في الأفكار وتطويرها. والجدير بالذكر أن النتائج كشفت أن الأفكار التي تلقت ردود فعل متباينة، تشمل القبول والرفض، تشير إلى صراع الفريق. يقدم هذا البحث رؤى قيمة حول ديناميكيات عمليات التفكير الجماعي، على الرغم من أنه من المستحسن إجراء فحص أكثر شمولاً للصراعات المحددة داخل الفرق ومقارنتها مع دراسات أخرى.

الكلمات المفتاحية: *الإدراك الجماعي، النموذج العقلي للفريق، نظام الذاكرة التفاعلية، التصميم التعاوني.*

1. Introduction

In recent decades, the design field has seen a surge in collaborative practices, driven by factors such as an expanding range of specializations and globalization's geographical spread. Technological advancements, such as the rise of optic fiber and 5G for data transmission, and novel digital tools for teamwork have also catalysed this shift. Given that teams bring a richer array of skills and knowledge than individual members (Levine and Choi, 2004), it's unsurprising that collaborative design teams have become increasingly prevalent. As globalization and competition intensify, design teams face growing pressure to produce unique and innovative designs. Typically, these teams invest significant time brainstorming a plethora of ideas to explore diverse design solutions. Yet, at some point, they must hone in on a singular vision. What informs the team's selection or rejection of these ideas? Drawing from team cognition theories, our study investigates how collaborative communication efficiency and media affordances impact decision-making. Team cognition (Wildman, Salas, and Scott, 2014) posits that team members have information vital for effective teamwork. Key concepts within this domain include the team mental model (TMM) and the transactive memory system (TMS), both believed to amplify team performance in the ideation phase by fostering communication and coordination. However, how TMM and TMS function during decision-making in this phase is not fully understood.

1.1. TEAM MENTAL MODEL (TMM)

The realm of team cognition has always grappled with terminology. Terms such as shared mental model and shared understanding abound, but for consistency, we use TMM. Converse et al. (1993) pioneered the TMM theory, which they described as “mental representations of objects, actions, situations or people." Numerous studies affirm the correlation between TMM and team performance. Essentially, TMM suggests that teams with a shared understanding of tasks and team members can better predict and cater to each other's actions, enhancing performance.

Within collaborative design, TMM has been deeply explored. Casakin and Badke-Schaub, as well as Goldschmidt (2007), have delved into its role in boosting team performance and creativity. They highlight three TMM variants: TMM-cohesion (focused on interpersonal aspects), TMM-task (centered on problems and solutions), and TMM-process (related to design procedures). Our research seeks to examine TMM's correlation with design team decision-making, leaning heavily on prior works for its operational definition.

1.2. TRANSACTIVE MEMORY SYSTEMS (TMS)

Wegner (1991) first introduced TMS as a "shared system for encoding, storing, and retrieving information" (p. 923). Its evolution since has been marked by twin approaches focusing on its cognitive and behavioral facets. On the cognitive front, TMS is seen as a shared understanding about specialization, credibility, and coordination among team members. Behaviorally, it's about updating directories, information allocation, and retrieval coordination. TMS's primary value lies in its ability to aid teams in problem-solving through access to vast information banks and quick recall. Early studies on TMS mostly centered on co-located teams. With the tech boom, research expanded to cover TMS's emergence in computer-mediated communication contexts. Some scholars even equate the internet to a universally accessible TMS. In the design sector, limited studies touch upon TMS's influence on team outcomes. In our study, we conceptualize TMS as the mechanism encoding, storing, and transferring novel ideas. Specifically, our research operationalizes TMS based on systems used for data storage and access, presentation platforms, modes of design representations, and media tools for design idea externalization. The tools employed included cloud storage, USB drives, projectors, whiteboards, computer desktops, sketches, text, digital images, personal journals, software applications, and the E-Beam Capture for whiteboard content digitization. For more details, refer to Dastmalchi, Balakrishnan, and Oprean, 2021).

2. Project Background and Data

Our research delved deep into the dynamics of a seven-member multidisciplinary design team, with their collaborative endeavors grounded in the nexus of contemporary spatial design and digital mediation (See D'souza and Dastmalchi, 2016). With diverse expertise spanning both traditional architectural realms and newer digital design paradigms, the team grappled with a unique design challenge: conceptualizing a 21st-century spatial or environmental intervention that reimagines how birthdays are celebrated. This directive, commissioned by a mid-western greeting card company, aimed to push the boundaries of conventional celebratory spaces, suggesting a shift from mere cards to immersive experiences.

This intricate design exercise spanned five rigorous days. Day one laid the conceptual foundation, introducing the team to the vast potential of space and interaction in celebration. The second day saw a 90-minute brainstorming session, where ideas transcended the paper, hinting at the seamless blend of physical and digital realms. Day three was a meticulous exercise in refining, reinterpreting, and categorizing these spatial narratives, a process that unraveled over four hours. The penultimate day was a deep dive into actualizing these spatial concepts, while the concluding day showcased these groundbreaking ideas at the company's architectural hub. A detailed chronology of events is tabulated below, with key data segments spotlighted for reference. Throughout this design marathon, every nuanced discussion and deliberation was captured across 15 video sessions, each lasting between 40 to 50 minutes. This study focuses on a 90-minute segment from the brainstorming day and the first 40 minutes of the refining day, pivotal moments of spatial decision-making. Complementing these videos are detailed transcriptions, screen captures, and personal design journals from each team member, painting a comprehensive picture of this architectural journey.

2.1. THE COLLABORATIVE ENVIRONMENT

This study utilized a collaborative setting, influenced by a system detailed by Balakrishnan and Oprean (2015). This system emphasizes the significance of design representation within the creative journey and its broader implications for a digital communication-supported collaborative space. The essence of such an environment is to leverage multimodal information to assist users in navigating the constraints of working memory, thereby enhancing learning and decision-making capacities. It's been long established in research that working memory has its limits, being able to hold only a restricted amount of information briefly. An overflow of information can hinder effective processing within this memory (Kalyuga et al., 1999). The team's primary workspace was a 12x8 foot digitally enhanced whiteboard that could display and share digital content using a graphics workstation. This setup was adept at recording digital interactions and annotations. All captured data was cloud-stored for easy access. Additionally, a projector was on hand for digital content display, and every team member was equipped with a computer.

3. Research Question and Method

Considering the importance of TMM and TMS in design communication and creativity, we wanted to know which aspects of TMM and TMS have a relationship with decision making towards the selection and elimination of ideas during the ideation phase. Using the framework from previous studies (Casakin and Basdke-Schaub, 2017; Gabriel and Maher, 2002), we examined the formation of TMM as a function of the team's verbal communication and interaction. Due to the nature of our data set, we used protocol analysis (Ericsson and Simon, 1993) to conduct our study. Two researchers coded the team discussions of each idea that contributed to the formation of TMM, using 'new ideas' as units of analysis. Therefore, our first research question was the following:

RQ1: Which aspects of TMM correlates with idea selection and elimination?

The foundation of this concept stems from the understanding that TMM primarily develops through verbal communication (Basdke-Schaub et al., 2007). When a new idea emerges, each team member might perceive it in their unique way, influenced by their background, cultural context, past experiences, objectives, expertise, among other factors. These elements crucially shape an individual's mental model within the team (Basdke-Schaub et al., 2007). Through deeper discussions about the idea and exchanging insights, the TMM takes shape. Consequently, the more an idea is deliberated upon, with team members exploring its various facets, the more aligned or 'shared' their mental model becomes concerning that idea. Here, "shared" refers to the degree of similarity or commonality in the mental models of team members. As such, ideas that undergo prolonged discussion are more apt to be retained in long-term memory (Fiore et al., 2003). Building on this understanding, we posited that ideas with a high degree of shared understanding (or alignment) would be more likely to be chosen. Essentially, the deeper and more extensive the discussion around TMM for an idea, the higher the likelihood of that idea being favored. This premise is rooted in our ability to access information in our long-term memory for more extended periods compared to data held in our working memory.

TMS was seen as a function of media affordances (Balakrishnan and Oprean, 2015). Different tools and media were available to the team to facilitate collaboration. We examined how different media affordances contributed to encoding, storing, and retrieving information; in other words, how did different tools and media as external memories contribute to the process of idea selection and elimination. By tracking each 'idea' throughout the design process, we coded how each idea was introduced; the modalities through which the idea was discussed, the presentation platforms used when the idea was discussed, and what system was used to store and access the idea. Therefore, we proposed the following question next:

RQ2: Which aspect of TMS correlates with idea selection and elimination?

In the realm of design, ideas are conveyed through various design representations, ranging from sketches to tangible models. These representations play a pivotal role in our communication processes, serving as repositories of information during the design evaluation phase. They essentially extend our cognitive capacities, acting as external storage for our working memory. Architectural understanding is inherently multimodal, often demanding an array of drawings and models to fully grasp a concept.

Research from the 1990s delved into the benefits of both multimodal and multimedia instructional methods. 'Multimodality' pertains to the utilization of multiple senses for communication, like text, sound, and visuals. On the other hand, 'multimedia' focuses on combination of various media formats, such as animations paired with narrations (Mayer and Sims, 1994). An illustrative study had participants understand the workings of a bicycle pump through varied instructional methods: animation combined with concurrent audio and text (group 1), solely audio and text (group 2), just animation without audio (group 3), and a control group with no formal guidance (group 4). Findings by Mayer and Anderson (1991) indicated that the first group exhibited superior performance compared to the others. Subsequent research pointed out that synchronously presented audio and visuals are more efficacious for learning and memory than when sequenced (Mayer and Anderson, 1992; Mayer and Sims, 1994).

Sundar (2000) further probed the interplay between memory and sensory modalities, designing an experiment that tested recall abilities across five conditions: text-only, text with images, text with audio, text combined with images and audio, and lastly, text, images, and video. Notably, participants excelled in the initial two conditions where text was the primary or sole medium. However, the research also implied that inundating users with multisensory inputs doesn't always enhance recall or decision-making and might sometimes serve as a distraction. Another intriguing study (Davis, et al., 2006) explored how varying modalities influenced jury decisions. Participants were exposed to suspect statements in text, audio, or video formats. The outcomes revealed that those who accessed the audio and video formats demonstrated heightened accuracy in their judgements, specifically in lie detection. These collective insights led us to hypothesize that integrating diverse tools and sensory channels when deliberating an idea could bolster its chances of selection.

4. Results and Discussion

Two coders utilized the INTERACT software for their coding tasks. The interrater reliability revealed $\kappa=0.72$ at the TMM level and $\kappa=0.93$ for TMS. The results presented here originate from a single case study, and we refrain from generalizing them. Our insights focus on the influence of various media capabilities serving as an external memory system (i.e., TMS) on team decision-making. We also analyzed the team's verbal interactions regarding TMM to discern any correlations with decision-making.

To examine our first TMS hypothesis, we conducted a Chi-Square test to determine differences between presentation platforms, communication methods, encoding mediums, and storage systems in relation to idea selection. Presentation platforms ranged from public to personal ones. Shared platforms, like projectors or whiteboards, were universally accessible within the collaboration area. In contrast, individual platforms required personal devices for access, such as viewing websites on desktops. Our assumption was that ideas from communal platforms would be more often selected. While no significant difference was found between idea selection and various platforms, our further analysis indicated a significant difference between ideas that were coded as ‘no platform’ and idea rejection.

For data transmission and storage, cloud storage prevailed over portable storage during ideation, influencing idea selection, X^2 (4, N=48) = 70.17, $p<0.001$. Regarding encoding media, journals and software for notetaking were utilized at an individual level. The E-beam medium, however, catered to the entire team, with its content being team-generated and cloud-accessible. Based on this, we speculated that E-beam-encoded ideas would be frequently chosen, a hypothesis supported by our results, X^2 (4, N=48) =75.49, $p<0.001$.

Sketching, as a communication method, was a significant indicator of idea selection, X^2 (1, N=37) = 69.78, $p<0.001$. There was no correlation between text or digital imagery and idea choice. Receiving multi-modal information can be a blessing and a curse, affecting memory either positively or negatively (Sundar, 2000).

Our subsequent hypothesis centered on the notion that ideas from the final session would differ significantly from previously chosen ones. Given the constraints of working memory, excessive information can hamper its processing efficiency, as per Kalyuga et al. (1999). In contrast, long-term memory accommodates more information over extended periods. Most of our selected ideas came from the second brainstorming session, with subsequent sessions producing fewer selections.

Using the point-biserial correlation test, we explored potential correlations between TMM-Task and TMM-Cohesion dimensions and idea selection. We identified correlations between discussion duration and idea choice, as well as revisiting and developing ideas. In terms of TMM-Cohesion, acceptance and rejection both correlated weakly with idea selection.

Remarkably, 26% of selected ideas received both approval and disapproval from different members, indicating significant team conflict. While research (Stahl et al., 2010; Jehn, 1995) shows diverse teams can experience both conflict and creativity, our case differed. Comparing our findings with others (Bierhals et al., 2007; Casakin and Basdke-Schaub, 2017), we noted that other teams surpassed ours in idea generation and TMM formation. However, a notable distinction in our study was using time (seconds) as a metric instead of frequency, which others employed. We believe time offers more precision due to the fluid nature of TMM. Nonetheless, discrepancies in team makeup and tools across studies warrant further examination.

The point-biserial correlation test was utilized to explore the potential relationship between the dimensions of TMM-Task, TMM-Cohesion, and idea selection. Given that the focus was on 'new ideas', the TMM associated with the process and some dimensions of other mental models, like those related to tools, environment, or interpersonal communications, were not pertinent to decision-making regarding idea selection. In the context of TMM-Task, there was a correlation between the total discussion time for an idea and its selection, with $r_{pb} = 0.35$, $p<0.05$. This correlation, though weak, was in line with our predictions. The incorporation of TMM into the structure of long-term memory within working memory gives insight into why extensively discussed ideas (towards a uniform TMM-Task) were more likely to be recalled and chosen. Re-examining an idea exhibited a weak correlation with idea selection, $r_{pb} = 0.35$, $p<0.05$, possibly due to the team's frequent revisitations during the selection phase. Often, revisits were made to justify an idea's selection or to query its feasibility. Moreover, the refinement of ideas had a moderate association with their selection, $r_{pb} = 0.40$, $p<0.05$. This suggests that ideas that were further fleshed out were more likely to be chosen, though the correlation remained moderate. Often, an idea was expanded upon by someone other than its proposer, signaling positive feedback. This leads us to the TMM-Cohesion aspect.

In the TMM-Cohesion realm, only acceptance, $r_{pb} = 0.35$, $p<0.05$, and rejection, $r_{pb} = 0.34$, $p<0.05$, showed weak correlations with idea selection. This indicates that both direct acceptance and rejection feedback from team members played roles in idea selection. While seemingly counterintuitive, a deeper dive revealed that out of 23 accepted ideas, 10 were endorsed by someone other than the idea's originator. Moreover, 6 of these 23 chosen ideas faced explicit rejection by team peers. Intriguingly, all 6 rejected ideas belonged to the accepted pool, meaning 26% of the chosen ideas received mixed feedback, highlighting team conflict.

While research has hinted at higher creativity in diverse teams despite increased conflict (Stahl et al., 2010), our findings deviated from this. Prior conflict studies indicate that conflict's impact hinges on its intensity, kind, and task nature (Jehn, 1995). A deeper dive into the specific conflicts within the team is warranted. Our results, when juxtaposed with studies like Bierhals et al., 2007 and Casakin and Basdke-Schaub, 2017, revealed that teams from other studies exhibited superior performance in idea generation and TMM formation. Notably, our study employed time (in seconds) as a metric for each code, while others used frequency. We deemed time a more precise measure due to the fluid and transient nature of TMM. Nevertheless, for comparison purposes, we also utilized code frequency. Further exploration is needed, especially when considering variations in team makeup, collaborative tools, and environments across different studies.

5. Conclusion

The overarching aim of this research was to unravel the association between Team Mental Models (TMM) and Transactive Memory Systems (TMS) with decision-making during the ideation phase. Both TMM and TMS, rooted in verbal communication, team interaction, and media affordances, play a quintessential role in shaping how ideas evolve and ultimately get selected or eliminated in design-centric tasks.

Starting with our exploration into the TMM, our results illuminated the criticality of team discussions in fostering an aligned understanding of ideas. It was discerned that prolonged deliberation upon an idea positively influenced its likelihood of being selected, substantiating our presumption rooted in memory theory. Specifically, the more an idea is discussed, the more entrenched it becomes in the collective long-term memory, making its retrieval and consequent selection likelier. This emphasizes the importance of maintaining a continuous discourse to foster collective understanding, ensuring that every team member's unique perspective is incorporated.

On the TMS front, the association of media affordances with decision-making was explored, pointing to intriguing findings. Although our presumption that communal presentation platforms would yield a higher idea selection rate wasn't significantly supported, our data did show that ideas lacking a specified platform were often discarded. The usage of E-beam mediums and sketching as communication tools was found to be robust indicators of idea selection. This supports the notion of multimodal and multimedia instructional methods' effectiveness. It should be noted, however, that inundating team members with too many modalities might detract from idea retention, aligning with Sundar's (2000) observation.

A curious observation made was regarding the conflicting feedback on selected ideas. While one might assume unanimous acceptance would be the primary criterion for idea selection, our data depicted that around 26% of chosen ideas encountered both acceptance and rejection. This ostensibly paradoxical finding adds nuance to the complex tapestry of team dynamics, hinting at the productive potential of conflicts. Research has long proposed that diverse teams, while more susceptible to disagreements, often produce creative outputs (Stahl et al., 2010). However, our findings somewhat diverge from this narrative, suggesting that while conflict can be constructive, its nature, intensity, and context matter immensely.

Comparing our results with studies such as Bierhals et al., 2007 and Casakin and Basdke-Schaub, 2017, we noticed discrepancies in idea generation and TMM formation capabilities. While these variations could stem from numerous sources, our unique metric of utilizing time rather than frequency might have contributed. Time, in our perspective, offers more granular insights given TMM's dynamic nature. However, it also raises the pertinent question: does the granularity of analysis influence the interpretation and subsequent application of findings?

In conclusion, our research underscores the intricate relationship between team dynamics, communication platforms, and decision-making in the ideation phase. While team interactions significantly mold the collective understanding and selection of ideas, the tools and media affordances used also play a non-trivial role. Future research can further delve into the nuances of team conflicts, dissecting their typology, and drawing correlations with decision-making. Moreover, the efficacy of time versus frequency as an analytical metric can be debated and tested across varied contexts.

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AUTHOR INDEX

AUTHOR INDEX

CLOSING NOTE

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As we draw the curtains on the 11th International Conference of the Arab Society for Computation in Architecture, Art, and Design (ASCAAD 2023), I stand before you again with gratitude and accomplishment. It has been an inspiring journey filled with thought-provoking discussions, innovative ideas, and valuable connections, all under the theme of "C+++: Computation, Culture, and Context." I would like to extend my heartfelt thanks to all our participants, speakers, and attendees. Your presence here has enriched the conference and contributed to its success.

I must also acknowledge the dedication and hard work of the organizing committee, without whom ASCAAD 2023 would not have been possible. Their tireless efforts, attention to detail, and passion for advancing the domains of architecture, art, and design have been truly commendable.

Over the past two days, we have had the privilege of witnessing the convergence of intellect, creativity, and vision. ASCAAD 2023 has indicated the power of collective wisdom, a reminder of the impact collaboration and interdisciplinary dialogue can have in shaping the future of our fields.

As we depart from this conference, let us carry forward the lessons learned, the connections made, and the inspiration gained. ASCAAD 2023 has been a crucible of ideas, where the past, present, and future of computation, culture, and context have been examined, dissected, and explored. The flashlight of knowledge has been passed, and it is up to each one of us to keep it burning.

Let this not be the end but the beginning of a journey to implement the insights gained into our respective practices and disciplines. Let us continue to bridge the gap between computation and culture, to design with sensitivity to context, and to create a world that is not only functional but also aesthetically and culturally enriching.

In closing, I want to express my hope that the connections made here will endure, that the ideas shared will flourish, and that the impact of ASCAAD 2023 will resonate throughout architecture, art, and design. Together, we have explored the possibilities of "C+++": Computation, Culture, and Context, and now it is time to carry these possibilities forward and transform them into reality.

Thank you all for your contributions, your passion, and your dedication to the advancement of our fields. I look forward to seeing the incredible work from this conference, and I hope to meet you again at future ASCAAD events.

Safe travels, and may your journey be filled with the knowledge and inspiration gained at ASCAAD 2023. Goodbye and take care!

Amer Al-Jokhadar
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ASCAAD 2023 Conference Chair
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The ASCAAD 2023 theme focuses on Computation, Culture, and Context; a triad that is increasingly informing and reshaping the emerging dynamics of design and construction in the built environment of several regions in the Global South.

The conference addresses the following sub-themes: Digital Heritage and Culture, Smart Cities and Buildings, Building Informatics and Parametrics, Digital Media and Generative Art, Virtual Realms and Multiverse Environments, and Performative-Driven Design and Digital Green.