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INTRODUCTION

We are pleased to present this volume documenting the scholarly contributions showcased during the second edition of the Digital Architecture Research Conference — DARe 2025. Held on 4–6 June 2025 at the Faculty of Architecture, Bialystok University of Technology, the event once again brought together researchers, doctoral candidates, and practitioners exploring the impact of digital technologies on architecture, design processes, and the transformation of the built environment.

The scope of this year's presentations — and of this publication — is broad. The contributions address topics such as parametric and computational design, BIM-based workflows, digital reconstruction of cultural heritage, generative and AI-driven design methods, automation in architectural and structural processes, 3D printing and robotic fabrication, sustainable materials and technological innovations, as well as architectural education and spatial experience in virtual and augmented environments. The 2025 edition also highlighted the inherently interdisciplinary nature of contemporary research, connecting architecture with material engineering, structural engineering, heritage studies, urbanism, and design pedagogy.

DARe 2025 reaffirmed that digital media and computational tools continue to reshape every stage of architectural practice — from conceptual sketching to prototyping, construction, and lifecycle management. Our goal for this edition was not only to showcase technological advancements, but also to encourage reflection on their implications: how tools influence design thinking, how they expand the boundaries of form and performance, and how they can support sustainable, responsible, and inclusive approaches to the built environment.

A particular emphasis this year was placed on supporting young researchers — especially PhD candidates — for whom the conference provides a platform to present ongoing work, engage in dialogue with experienced scholars, and gain visibility within the international research community. We believe that their fresh perspectives, often unconstrained by established conventions, are essential to the future development of digital architecture research.

The contributions collected in this volume reflect the spirit of DARe — a spirit of openness, experimentation, interdisciplinarity, and critical inquiry. Some of the papers investigate emerging materials and construction technologies; others explore the potential of AI, VR, and AR to rethink spatial experience; still others critically examine what is gained and what might be lost as architecture becomes increasingly shaped by computation.

We hope that this publication will not only enrich academic discourse, but also inspire future generations of researchers, practitioners, and educators — those who, like us, see architecture as more than form: as a field where technology, ideas, people, and context converge.

LEVEL UP SUSTAINABILITY: A VR-BASED GAMIFIED APPROACH TO MATERIAL CHOICES IN INTERIOR ARCHITECTURE EDUCATION

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ABSTRACT:

Gamification and Virtual Reality (VR) technologies are transforming design education to close the theory-practice gap and real-world problems like sustainability. This paper suggests an interactive VR-based game to immerse interior architecture students in the assessment of sustainable wall materials for interior spaces. Four common materials—reinforced concrete, autoclaved aerated concrete (AAC), brick, and gypsum—are the basis for the simulation, which optimizes environmental footprint, life-cycle analysis, and resource efficiency. Within the VR environment, students could construct and compare various wall assemblies in real time and receive dynamic feedback on embodied energy, carbon footprint, and end-of-life disposal. Through gamified elements such as scoring and interactive challenges, the platform increased motivation and encourages a more nuanced appreciation of the ways that materials impact not only design outcomes but ecological footprints as well. This method enables students to try out various configurations without the physical constraints or expense that may be involved with conventional models of learning. Initial results are that fully immersive simulations promote better recall of sustainability principles and improve required critical thinking in terms of detailing eco-friendly materials. Also, by providing students with control over live decision-making, the VR game provides a risk-free learning experience that simulates the real process of design quite realistically. The research concludes that while the application of VR and gamification has the potential to enhance sustainability literacy in interior architecture education, this impact strongly depends on how these technologies are integrated—requiring carefully designed, interactive, and context-driven experiences that embed environmental data meaningfully into design processes and decision-making tasks. Future directions will include more advanced analytics and multi-sensory feedback to continue to bridge academic instruction and professional practice and global environmental aspirations.

Keywords: Virtual Reality, Gamification, Design Education, Interior Architecture Education, Sustainability.

1. INTRODUCTION

In the past decades, sustainability has emerged as one of the central components of interior architecture education due to increasing global awareness regarding environmental degradation and the role of the built environment in climate change. As future interior environment designers, interior architecture students are not only required to be technically and aesthetically proficient but also make informed decisions regarding sustainable material usage and construction practices. Traditional pedagogic methodologies—primarily based on two-dimensional sketches, lectures, and texts—are generally insufficient in enabling students to better comprehend the full ecological consequences of their material choices.

As a means of bridging theoretical sustainability knowledge with real-world design practice, virtual technologies such as Virtual Reality (VR) have gained widespread popularity in the teaching of architecture and design. VR offers unique chances to simulate reality in lab-like environments where students can experiment, make decisions, and observe consequences in real time. With gamification techniques layered on top of VR—applying scoring systems, interactive missions, and choice-driven feedback—VR is now a highly potent learning tool that not only conveys information but also stimulates more engagement and critical thinking.

This article introduces a VR-supported learning game to cultivate students' sustainability literacy in interior architecture through simulating the assessment of four common wall materials: reinforced concrete, autoclaved aerated concrete (AAC), brick, and gypsum. In the VR environment, students explore wall assemblies interactively and receive real-time feedback on parameters such as carbon footprint, embodied energy, and material lifecycle effect. The objective of this research is to determine the effectiveness of the integration of sustainable ideas into a VR-based learning setting in augmenting learners' understanding, memorability, and interest in course work choice for sustainable interior construction. Through analysis of participant experience and pilot study comments, the aim of this paper is to achieve an understanding of how gamification and VR can bridge the theory-practice gap in sustainability education, and make suggestions for designing future immersive tools for interior architecture courses.

2. LITERATURE REVIEW

This section presents a review of existing literature on three complementary themes: sustainability in studies of interior architecture, application of virtual reality in design education, and application of gamification in sustainability.

2.1 Sustainability in Interior Architecture Education

Integrating sustainability into interior architecture education has become a crucial approach for preparing students to tackle environmental, social, and economic issues within the built environment (Burkut, 2023). Recent evaluations underscore the necessity for courses that incorporate lifetime assessment, bio-based materials, and indoor environmental quality to promote comprehensive and context-specific design thinking (Yıldırım & Erdoğan, 2023; Mdpi, 2023). Case studies, including those focused on courses in Turkey, illustrate that active, industry-connected learning frameworks substantially enhance student knowledge and implementation of sustainable design concepts in studio projects (Afacan, 2013).

2.2 Virtual Reality in Design Education

In design education, virtual reality is widely acknowledged as an effective instructional instrument that improves spatial comprehension, engagement, and critical analysis among students. In interior and architectural contexts, immersive virtual reality environments have demonstrated enhancements in collaborative learning, design reflection, and technical proficiency in early-stage design courses (Greer, Meggs, & Collins, 2012). Systematic reviews underscore VR's ability to facilitate real-time interaction and experiential learning via immersive audiovisual experiences in game-like settings, which enhance constructivist engagement and augment spatial cognition (Doktah Mokhtar et al., 2023; Lampropoulos & Kinshuk, 2024). Empirical studies indicate that the incorporation of VR supplements with conventional studio instruction results in substantial improvements in students' technical and spatial understanding, as well as increased motivation and user happiness (Olbina & Glick, 2022; Li, 2024). Furthermore, mixed-methods research demonstrates that VR-based gamified learning markedly enhances understanding of building systems, energy efficiency, and construction techniques via interactive and puzzle-oriented learning environments (ArbesserRastburg et al., 2024). Comparative analyses of VR, video walkthroughs, and physical site visits indicate that immersive VR significantly improves layout retention and spatial recall, surpassing conventional methods (Tüker & Tong, 2021).

2.3 Gamification for Learning Sustainability

In recent years, gamification has become an effective technique for improving sustainability education in design and built-environment fields by converting abstract concepts into engaging, practical learning experiences. Gamified frameworks, including board games and immersive escape-room situations, have shown substantial improvements in environmental awareness, motivation, and cognitive retention among various learner demographics (Dudok & PigniczkiKovács, 2023; Van Maurik & Hostettler, 2019). In educational contexts, game design elements—such as points, badges, challenges, and immediate feedback—have demonstrated the ability to close the frequently observed divide between sustainability knowledge and sustainable behaviors by fostering intrinsic motivation and contextual decision-making (Van Maurik & Hostettler, 2019; MDPI, 2023). In the realm of interior architecture and design education, pilot studies utilizing experiential learning cycles have demonstrated that meticulously designed gamified activities markedly enhance student engagement, collaborative learning, and understanding of material and structural sustainability issues (Mehelmy & Zeini, 2024). Moreover, extensive evaluations of gamified interventions in built environment education confirm that simulation and puzzle-oriented game mechanics can affect energy-conscious design perspectives and habit development among upcoming professionals.

3. METHODOLOGY

This section delineates the methodological framework employed in the development and assessment of the VR ConstructED game. A qualitative research design was utilized to obtain comprehensive insights into participants' experiences and perceptions concerning the tool's usability, educational significance, and its contribution to enhancing sustainability consciousness. The research engaged a pilot cohort of interior architecture students who interacted with the VR simulation and offered feedback via semi-structured interviews. The subsequent subsections elucidate the research strategy, participant demographics, data gathering methodologies, and technical specifications of the VR tool.

3.1 Research Design

This research employs a qualitative case study methodology to investigate the impact of a virtual reality game-based simulation on sustainability awareness and material choosing competencies in interior architecture education. The research approach is based on the interpretivist paradigm, emphasizing the comprehension of participants' lived experiences, perceptions, and meaning-making processes within an immersive virtual reality environment. The main objective is to investigate how sustainability principles, including environmental impact, embodied energy, and life-cycle assessment, may be effectively conveyed using interactive and gamified virtual reality mechanisms. The research used a pilot intervention strategy, introducing a bespoke VR game named "VR ConstructED" to participants. This game engaged students in a simulated design scenario necessitating decisions on wall material selection. The study seeks in-depth conceptual insight into the educational impact of immersive sustainability-oriented events rather than statistical generalization. A thematic analysis approach was employed to understand the data, facilitating the identification of recurring themes and patterns in the participants' input. Themes were employed to assess the efficacy, usability, and instructional clarity of the VR tool, specifically on its depiction of sustainable design principles.

3.2 Participants

The participant group comprised five fourth-year interior architecture students from faculty of architecture and design. The students were chosen by purposive sampling due to their existing core knowledge in construction techniques and material science, despite not having completed a formal course in sustainability. The limited, concentrated sample size corresponds with the exploratory character of the study, facilitating comprehensive, nuanced input via individual interviews. All participants possessed moderate to advanced proficiency with digital tools typically used in architecture education (e.g., SketchUp, AutoCAD), although none had prior exposure to VR-based sustainability simulations. The study received ethical approval from the university's ethics board, and all participants gave informed consent before participating in the VR experience.

3.3 Data Collection

Data was gathered via two complementing qualitative instruments consist of semi-structured interviews and observation notes. Each participant participated in an individual interview following the VR session, which lasted from 25 to 40 minutes. Interview inquiries centered on perceptions of sustainable integration, user experience, visual clarity, interactivity, and overall educational outcomes. A targeted inquiry was incorporated to solicit feedback regarding the utilization of tables and data visualization in conveying environmental impact (e.g., carbon footprint, embodied energy). During the session, participants' interactions with the virtual reality environment were recorded and analyzed. Focus was directed towards participants' voluntary engagement with sustainability data, their responses to visual feedback mechanisms, and their material selection processes inside the gamified simulation. The interviews were audio-recorded, transcribed, and analyzed to facilitate thematic categorization and interpretation.

3.4 The VR Tool: VR ConstructED

The VR simulation created for this project, VR ConstructED, is a gamified, immersive application developed with Unreal Engine 5.5, specifically intended to educate users on sustainability concepts in material selection for wall assembly. The tool enables students to compare four prevalent materials: reinforced concrete, autoclaved aerated concrete (AAC/Ytong), brick, and gypsum, using an interactive, scenario-driven interface.

The VR game's development process adhered to a three-phase digital workflow. Initially, two-dimensional construction drawings of wall sections and material arrangements were created using AutoCAD. The technical drawings were subsequently imported into SketchUp to create precise 3D models of walls and building elements, assuring scale precision and architectural consistency. The models were refined and sent to Unreal Engine 5.5, where the immersive and interactive elements of the simulation were integrated. In Unreal Engine, interactivity, material properties, gamification components (e.g., scoring, feedback), and environmental configurations were programmed via Blueprint visual scripting. Virtual reality integration and testing were performed utilizing the Meta Quest 3 headset. This cross-platform approach facilitated a quick transfer from technical documents to a fully immersive, real-time experience that authentically replicates construction situations with sustainability-focused options.

Figure 1: General overview of the VR game designed in Unreal Engine 5

The VR tool integrates multiple essential aspects aimed at improving sustainability-focused education in interior architecture. It provides real-time simulation of wall building, delivering rapid feedback on essential sustainability metrics including embodied energy, carbon footprint, and recyclability. Gamified obstacles are integrated into the experience, necessitating users to make environmentally responsible material selections within time limits or to attain specified sustainability score objectives. In the virtual environment, graphic tables depict the environmental implications of materials, accompanied by concise animations and aural signals to enhance learning.

Figure 2: Full-scale construction area showcasing all wall materials in a single structure

Figure 2 illustrates a virtual mock-up in the VR learning environment, demonstrating the cohesive use of several wall building techniques inside a singular structure. This structure enables users to analyze and contrast various materials such as reinforced concrete, brick, AAC blocks, and metal drywall framing within their authentic spatial context. The skeletal structure and partial sheathing offer an internal perspective, enhancing comprehension of the layered assembly procedure.

Figure 3 displays a chart of sustainability concepts integrated into material rooms of the VR game. The graphic visually contrasts different wall building materials according to essential sustainability factors,

Figure 3: Sustainability principles chart in the brick material zone

including embodied energy, carbon footprint, thermal performance, and recyclability. Situated centrally inside the virtual environment, it functions as an educational reference, enabling students to critically evaluate and contrast content selections about their environmental consequences. This tool facilitates informed decision-making by directly connecting material choices to sustainable learning objectives.

4. FINDINGS

Comments from respondents reflected passion and critical consideration of the application of sustainability principles to the virtual reality learning environment. One of the most powerful observations was that presentation of sustainability data in static form particularly in the form of conventional tables was not deemed adequate in the interactive nature of virtual reality. As one student put it, "I glance at the table, I read it, and although it exists in three-space, it is still only text that's cast upon a two-dimensional plane." This kind of observation assumes that even though information is nominally located within a VR environment, it fails to leverage the medium's immersive, experience-based qualities. Students offered a need for more interactive and engaging presentation of content, such as "an animation illustrating environmental impacts," which they believed would make learning about sustainability more effective and memorable.

Active engagement was repeatedly reinforced. One of the respondents mentioned that "if the user is to lay bricks with mortar, then a short instructional video could demonstrate how it is done in real life," which suggests a need for embedded, context-triggered feedback rather than passive reading. Similarly, another participant emphasized, "information should not just be displayed in one place as text but should be organically integrated into the experience," advocating for an interaction model that aligns educational content with hands-on learning. These comments underline that the simple presence of sustainability data is insufficient unless paired with interactive, decision-based learning experiences.

Several students reflected on the necessity of balancing educational depth with user effort. Someone commented, "learning should cost an effort, and obtaining information should cost an engagement," implying that people need to click buttons, move towards content, or do something in order to discover sustainability information. This resonates with another student's statement: "It is, in a way, an investment of effort," which is a nod to the idea that cognitive and physical effort enforces learning. Furthermore, the complaint that "no one is going to take the time to read a long, text-heavy chart" refers indirectly to a problem: that presenting students with an enormity of static material in an immersion-friendly platform stifles motivation and memory.

There were respondents who lingered on the balance between learning and entertainment. One commented, "There is a danger of going from education to entertainment, so there must be a clear boundary," but also acknowledging that animated feedback would "make the experience much more impactful." This middle-ground position reflects that while learners welcome immersive material, they are wary of gamification mechanics dominating the learning goals. The suggestion of offering "a 20-minute version, a 40-minute version, and even an extended 1.5-hour version" of the VR game displays that students prefer adaptable formats that can be molded in response to varied skill levels and learning needs.

Figure 4: General design of the material rooms

Finally, students emphasized that abstract information on sustainability must be made meaningful through functional and spatial context. One of the users noted the manner in which "some text is not legible from a distance but becomes clear when viewed up close," recognizing this as not a failing but a choice made for encouraging active exploration. Another user stated, "if I had attempted to read those tables, it would have taken probably quite a while," suggesting that sustainability content must be simplified and more graphical to accommodate the VR environment. The need for scalability, tailored speed, and openness to how sustainability is managed in an architectural framework was a recurring theme throughout answers.

5. DISCUSSION

This study's findings highlight the complex relationship between immersive learning, interactivity, and the dissemination of sustainability principles in a VR educational setting. Participants constantly underscored that for sustainability education to be effective in virtual reality, material must be seamlessly integrated, presented visually and contextually, and necessitate active user participation. Conventional techniques like static data tables or disjointed overlays proved insufficient, frequently disrupting immersion and cognitive continuity. Learners favored sustainability content that is physically integrated into the environment, sensitive to their actions, and enhanced by dynamic feedback mechanisms. This input indicates a fundamental change in the communication of intricate environmental concepts: they should be presented not as static data points, but as components of an active, exploratory, and experiential learning process. The subsequent sections detail these expectations, emphasizing design solutions that enhance engagement, augment knowledge retention, and link gamified elements with instructional goals within sustainability education.

5.1 Tables Must Be Converted into Visual-Audio Components:

Participants consistently described how static, text-based sustainability tables did not function within the VR setting. The very dense format of traditional data displays such as charts outlining embodied energy or carbon footprint was found to be cognitively overwhelming and inappropriate for the immersive nature of virtual environments. They suggested using dynamic visual aids, including diagrams, icons, and brief animations, to display complicated environmental data in a more natural way. The participants emphasized that such visualizations should be activated contextually, i.e., if a student selects a specific wall material, an animation may automatically show the environmental impact of that material along its life cycle. Short audio-visual indications and verbal commentary were also proposed as a solution in place of extensive written text, particularly for those students who might have difficulties with reading comprehension in paced or immersive settings.

5.2. Integration Should Appear Seamless, Not Disruptive:

One recurring motif in participant feedback was that sustainability information had to be embedded organically within the flow of the VR experience. Where environmental information manifested as discrete overlays or external panels, it had a tendency to be perceived as disruptive and disconnected from the spatial narrative. Players advocated for an embedded approach whereby information such as energy usage or carbon footprint is presented as part of the interaction—an example being a graphical cue or animated overlay that directly manifests within the 3D space when a player interacts with or selects a building material. Through contextual embedding of content, the game maintains immersion while still communicating critical educational content. This approach ensures continuous and consistent learning, in accordance with user expectation of spatially adjacent content in immersive environments.

5.3. Active exploration is essential for learning:

People communicated that data regarding sustainability must be actively found, not simply passively consumed. Being passively shown a table or a quick look at a chart was not sufficient for knowledge retention. The VR space, in order to effectively teach about sustainability principles, must cause intentional behaviors on users like dropping objects, viewing performance comparisons, or triggering focused content by manipulating building components. These interaction loops transform students into active agents rather than passive recipients. For example, rather than being taught about the carbon footprint of reinforced concrete, students may be presented with a task that asks them to build a wall using this material and experience its environmental effect in the simulation immediately. This form of embodied cognition consolidates conceptual knowledge by action.

5.4. User Effort Equates to Enhanced Learning:

One of the strongest results was the interaction between effortful thinking and learning depth. Respondents maintained that information about sustainability is more memorable if users have to struggle to access, compare, or evaluate information, rather than simply view it. The design of the VR experience should therefore include decision nodes or gamified activities that require learners to consider environmental impacts such as choosing between two materials with different environmental histories. Such decision-making scenarios are realistic to represent architectural problems and are best suited to reflective learning. Rather than simply providing the "correct answer," the system must encourage learners to decide, observe the results, and infer from experience.

5.5. Educational Objectives Must Not Be Diminished by Amusement:

While the VR game was interesting for participants, they valued education over fun. Scoring mechanisms or color-coded responses were helpful as learning aids but were perceived to detract from sustainability objectives when employed for leaderboards or fun activities. Feedback shows that gamified elements must be intentional and supportive of the instruction message, rather than substituting for it. It is necessary to find a fine balance between pedagogy and interactivity in an attempt to engage students closely with environmental learning goals without distracting them from shallowness of game mechanisms.

5.6. Information Must Be Scalable According to Temporal Factors and User Proficiency:

Individuals had varied preferences with regard to the size and duration of the VR learning experience. Some enjoyed concise, lean sessions with sharp sustainability data, while others preferred longer, in-depth investigations. This is a testament to the need for scalable material that can accommodate divergent levels of experience and learning pace. The VR system must be able to support tiered modes, e.g., a basic 15-minute scenario for first year students and an elite 40-minute simulation for advanced learners. Such a modular approach offers access as well as provides higher immersion when user expertise improves.

5.7. Content Delivery Must Employ Spatial Hierarchies:

Spatial accessibility was identified as an important design factor. Several participants complained of struggling to read text or observe information panels placed too high, too low, or at awkward angles within the VR environment. These issues resulted in physical discomfort and reduced learning effectiveness. To counter this, the VR tool must adhere to spatial hierarchy principles, positioning key insights within ergonomic proximity and best viewing angles. Text and graphics should be in the user's line of sight, at a suitable scale, and positioned such as to avoid unnecessary movement and confusion. Such considerations are especially important in educational VR settings where students are highly reliant on visual information for learning.

5.8. Feedback and result loops must incorporate environmental repercussions:

Students encouraged the application of instantaneous and material feedback mechanisms to demonstrate the impact of sustainability decisions. When a student selects a material, the system needs to reflectively indicate that choice in real-time measurements such as a visual cut in carbon footprint or an animated representation of environmental destruction. The dynamic components replicate cause-and-effect and help learners understand the tangible outcomes of their design choices. Feedback loops not only expand interaction but also provide robust reinforcement of sustainability concepts, anchoring abstract information into something concrete and actionable.

5.9. Curiosity and Advancement Should Be Associated with Sustainability Education:

Students favored systems that rewarded curiosity and experimentation highly. They wanted the ability to experiment with "what if" situations and see what different choices led to different environmental outcomes. This implies the need for branching pathways in the development of the VR game, whereby sustainable decisions unlock additional content, interactive experiences, or greater visuals. By linking curiosity with progression, the system rewards intrinsic motivation while guiding learners toward deeper engagement with sustainability issues.

5.10. Contextual Learning Enhances Material Retention:

Abstract sustainability data e.g., “low embodied energy” were typically described as not memorable unless grounded in a narrative or functional context. Participants suggested that placing information within realistic scenarios, e.g., building failure or energy inefficiency caused by material selection, would make sustainability lessons more memorable.

6. CONCLUSION

This study explored student perceptions of how sustainability concepts were integrated into a VR-based educational tool for interior architecture. Findings suggest that while the inclusion of environmental data is a necessary and valuable component of construction education, the method of delivery significantly influences its impact. In summary, the application of VR and gamification has significant potential to enhance sustainability literacy in interior architecture education. However, achieving this requires thoughtful integration of content, clear instructional scaffolding, and a commitment to experiential, student-centered learning design. Future development efforts should prioritize visual clarity, interactivity, and pedagogical alignment to ensure that VR tools effectively support sustainable thinking among design students.

REFERENCES

Afacan, Y. (2013). Introducing sustainability to interior design students through industry collaboration: A case study from Turkey. *International Journal of Sustainability in Higher Education, 14*(4), 454–465. researchgate.net+1dergipark.org.tr+1

ArbesserRastburg, G., Safikhani, S., Gustin, M., Hopfe, C., Schweiger, G., & Pirker, J. (2024). *Project Beyond: An escape room game in virtual reality to teach building energy simulations.* arxiv.org

Burkut, E. B. (2023). Literature review and analysis of publications on sustainability & sustainable design in interior architecture & interior design. *Kent Journal, 16*(4), 2672–2689. dergipark.org.tr

Doktah Mokhtar, M. N. A., Ismail, I., Wan Hamzah, W. M. A. Fazamin, & Amin, M. M. (2023). *Systematic literature review of interior design in virtual reality environment.* pmc.ncbi.nlm.nih.gov+9pdfs.semanticscholar.org+9academia.edu+9

Dudok, F., & PigniczkiKovács, E. (2023). Education for sustainability through gamification. *Acta Cultura et Paedagogicae*. researchgate.net

Greer, A. G., Meggs, S., & Collins, S. (2012). Virtual reality in interior design education: Enhanced outcomes through constructivist engagement in Second Life. *International Journal of Web-Based Learning and Teaching Technologies*, 7(1), 19–35. academia.edu+1researchgate.net+1

Greer, A. G., Meggs, S., & Kibbe, S. (2011). Virtual reality in interior design education: Enhanced outcomes through constructivist engagement. *Journal of Interior Design*, 36(1), 115. researchgate.net

Lampropoulos, G., & Kinshuk. (2024). Virtual reality and gamification in education: A systematic review. *Educational Technology Research and Development*, 72, 1691–1785. link.springer.com

Li, Z. (2024). *The practice of virtual reality technology in interior design education and the cultivation of artistic design thinking. Applied Mathematics and Nonlinear Sciences*, 9(1), 1–15. pmc.ncbi.nlm.nih.gov+15researchgate.net+15academia.edu+15

MDPI. (2023). Gamified learning for sustainability: An innovative approach. *Sustainability*, 17(6), Article 2694. papers.academic-conferences.org+15mdpi.com+15researchgate.net+15

Mehelmy, D. E., & Zeini, I. E. (2024). Experiential learning through gamification in interior architecture and design. *International Journal of Architecture, Arts and Applications, 10*(2), 42–59. sciencepublishinggroup.com+1researchgate.net+1

Motta, F., Carrasco, A., Romero, M., & Tarrega, S. (2025). A systematic review of gamified interventions in sustainable built environments. *Science of the Total Environment*. sciencedirect.com

Olbina, S., & Glick, D. (2022). Virtual reality as a supportive tool for design education: An experimental study in architecture. *ERIC Journal*, files.eric.ed.gov

Tüker, C., & Tong, T. (2021). Comparing field trips, VR experiences, and video representations on spatial layout learning in complex buildings. *arXiv*. arxiv.org

Van Maurik, B., & Hostettler, Y. (2019). Gamification for sustainability. (Master's thesis, DIVA Portal). upcommons.upc.edu+15diva-portal.org+15mdpi.com+15

Yıldırım, Y., & Erdoğan, M. (2023). Exploring sustainability in interior design: A comprehensive systematic review. *Buildings, 14*(8), Article 2303. mdpi.com

TECHNIQUE OF DISJUNCTION

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Abstract:

This paper examines the concept of disjunction in architectural discourse in relation to contemporary design methods of adaptive reuse. Through literature review and a series of experimental design projects, the relevance of disjunction to adaptive reuse and its representation technique are investigated. In addition, its evolution in the formal languages of the 21st century is explored.

The study is grounded in the use of 3D digital modeling to challenge drawing conventions tailored to the cognitive intersection of form and function within a fundamentally functionalist framework. Such a multidimensional approach is crucial to conceptualize disjunctions and transform conventional representations, such as elevation and plan drawings, into unfolded and juxtaposed models.

The study commences with the observation of spolia fragments reincorporated in new building designs. This argument draws upon important architectural concepts from the 1970s that investigated formal languages derived from effects of disjunction. These concepts, initially

borrowed from the field of philosophy, serve as foundational references for this argument: Bernard Tschumi's introduction of disjunction pioneered the field of architectural semiotics through his Manhattan Transcripts (1976-1981). Peter Eisenman explored the syntactic system of disjunctive imagery in his project, House X (1975-1982). Arata Isozaki recontextualized the meaning of disjunction into disjunctive synthesis through multiple projects from the 1970's to the 1980's. These position share the notion of disjunction as a design technique that disrupts conventional relationships between form and function, aligning with ideas of discontinuity, disaggregation, and fragmentation. By controlling edge conditions between formal representations, the languages of disjunction invite users to diverse realities from historical to virtual embedded in the fragments.

Disjunction is a particularly relevant concept in contemporary architecture, which is increasingly focused on adaptive reuse projects. While adaptive reuse has attracted significant research related to economics, social programs, culture, and building performance, research explicitly focusing on architectural aesthetics — and more precisely, the effects stemming from new relations of building fragments or parts — seems to be less common. Additions to built environments and as-found conditions necessarily integrate diverse formal languages that superimpose and transform existing relations of form and function. In this sense, the complexities that arise from the act of continuing (weiterbauen) demonstrate great potential for further developing architectural language and representing diversities in which buildings communicate with the city through evolving and merging languages.

This paper recontextualizes disjunction within 21st-century urbanism, emphasizing its role in adaptive-reuse beyond practical design approaches. It examines experimental research projects that embody the concept of disjunction, emphasizing its importance in contemporary architectural practice, particularly in adaptive reuse. It should be noted that these arguments are made by architectural designers, not historians. Nevertheless, the narratives will attempt to recontextualize design projects within architectural history and current phenomena in a logical manner.

Keywords: Form, Function, Disjunction, Spolia, Fragment, Representation

1. INTRODUCTION

In the 21st century, the formal complexity of buildings increases, particularly in adaptive-reuse projects that respond to sustainability concerns. Such projects often reassemble spolia fragments into new formal languages, constructing a historical fiction beyond historical preservation. Whereas the design language of these fragments integrates diverse forms into a new assemblage, their original functions are often dismissed—yet overwritten as part of a fictionalized narrative. Through these reassemblages, historical fiction facilitates a richer contextualization across different times, places, and cultural backgrounds—something that would have been difficult to achieve through either pure preservation or entirely new design alone.

> Spolia refers to artefacts procured from dilapidated buildings to be integrated into novel structures, where they may uphold their original function or acquire an alternative purpose in accord with their new environment (Gönül, 2023, p.157).
> Also, the term [Spolia] is now loosely associated with notions such as the fragment, reuse, and recycling, and it may range from a single ornamental or structural element to a whole building or part of a building (Rabaça, 2022, p.42).

From an aesthetic point of view, the new assemblage expresses a harmonious whole stemming from incongruent parts. The combination of old and new parts in an incongruent or inconsistent way positions architectural design within the context of constant historical change. "Time-Binding" (Jencks, 2011, p.166) or "time-junctures" (Goffi, 2016, p.31). Whether distinctive discrepancy or seamless transition, the formal aesthetics of this new harmony represents the heterogeneous condition of the world.

1.1 Adaptive-reuse of today

Although widely dismissed during the 20th-century modernist era, adaptive reuse and the superimposition of spolia has been a constant throughout architectural history. A few comparably recent examples from this rich history must suffice for this argument.

From the 1960s to the 1970s, Carlo Scarpa engaged in what we would like to contextualize as the construction of historical fictions, such as the Museo di Castelvecchio (1964) in Verona and the fountain design next to the main gate of the Università Iuav di Venezia. In "Built Conservation and the Unfinished Fabrics of Time" (2016), Federica Goffi analyzed Scarpa's approach to historical precedents as critical and fictional in contrast to conventional restorations (p.29). Goffi claims that this fictional method of historical recourse derives from the Renaissance, when the meaning of restoration was much closer to "give a new beginning" (p.29) than to fixing a building as it was.

> Recycled historical elements [of Castelvecchio] were reused to create a mock-up of history, creating a past that could have been, but never was (p.29).

In 2000, Enric Miralles incorporated fragments of a demolished building into his extension project for the Utrecht Town Hall. The project was widely critized for its alleged a lack of taste and labeled as "collage-architecture" (p.71). However, in his essay "Municipal Entente: Town Hall, Utrecht" (2002), Peter Blundell Jones claims that Miralles used the aesthetics of fragmentation to establish continuity. The existing buildings had already been collages of multiple styles such as Gothic, Renaissance, and Neoclassicism (p.71).

> The coexistence of preserved, recovered and added elements offers a singular reinterpretation of history in recognizable 'episodes', through which citizens from different generations are able to feel identified (p.76).

In 2007, Peter Zumthor integrated multiple architectural fragments into his design for Cologne's Kolumba museum: A homogeneous brickwork volume based on Roman masonry bond integrates spolia from diverse origins, including the foundations of the original Romanesque and partial walls of Gothic St. Kolumba church as well as Gottfried Böhm's post-war chapel, "Madonna in den Trümmern".

> Another 'time-building' made from fragments of six periods and given a protective cover by Zumthor's unique grey masonry. This custom-made brick allows in a dappled, atmospheric and dim light over the archaeological site surmounted by a contrasting zigzag bridge. A hybrid museum-shrine to a generic spirituality (Jencks, 2011, p.171).

2. COMPLEX ADAPTIVE SYSTEM BEYOND ANTI-COMPLEXITY THEORIES

In "The Story of Post-Modernism: Five Decades of the Ironic, Iconic and Critical in Architecture" (2011), Chales Jencks describes today's concept of architecture and city as "Complex Adaptive System" (p.187) that often includes the "recycling of the old building[s]" (p.21) where the old and new are stitched into a difficult whole. He notes that theories of complexity in postmodern architecture emerged somewhat competitively from the 1960s to the 1980s.Generally, these theories rejected the modernist idea of utilitarian architecture based on functionalism. However, toward the end of the 20th century, postmodern ideas about complexity theories came under criticism. In an increasingly pluralistic architectural discipline, the concept of complexity related to science-oriented, modernist architecture collided with an interest in intricacy related to postmodernist thought such as diversity, collage, or pre-exiting form.

> As a complex adaptive system it goes through several lives and deaths, several technical re-births as it adapts to the marketplace. Thus re-construction, re-flection and re-invention - the 're-s' - characterise the constant recursion, the artefact created in endless feedback (p.187).

Accordingly, from the perspective of American neoliberalism and architectural critique, Jeffrey Kipnis argues in "Toward a New Architecture" (1993) that postmodern complexity theories—like collage and montage—became obsolete. These strategies were only effective in questioning the dominance of modernist ideals of consistency and simplicity (p.100). In response, Kipnis proposes a "New Architecture" (p.102) centered on "folding" (p.105), a smooth, topological form. He cites projects such as Shirdel and Zago's Alexandria Library, the Columbus Convention Center of Peter Eisenman, and Gehry's Vitra Museum as early examples opposing the fragmented language of deconstructivism (p.106).

From the standpoint of English conservatism and mathematical scientism, Nikos A. Salingaros critiques postmodern deconstruction in

Anti-Architecture and Deconstruction (2004; 2007; 2008; 2014). He repeatedly discredits Jencks's *The Language of Post-Modern Architecture* and, with influence from Christopher Alexander, frames deconstructivist theories as a "cult" or "virus" lacking scientific grounding. Instead, Salingaros argues that true architectural complexity lies in "geometrical order" (p.30)—simple box forms arranged like a "chessboard" (p.29)—rather than in visual or stylistic fragmentation (pp.29–30).

From an existential and phenomenological perspective, Valerio Olgiati's *Non-Referential Architecture* (2013) rejects the cultural and conceptual frameworks of postmodernism. He argues that contemporary architecture must be "purely architectonic" (p.14), having lost ties to function or cultural meaning. Instead, architecture should evoke a "basic feeling" inherent in all humans—independent of social or technological references. Thus, postmodern ideals like multiplicity, heterogeneity, and decentralization have no place in design (pp.13–19).

After three decades of criticism, the question arises as to why a theory of complex adaptive systems is necessary for understanding current architectural practice. Today, architects have recognized their responsibility for the sustainable use of resources, and their work necessarily aims to preserve them. Therefore, an interest in strategies of intricate relations is not just another formalist theory. It is the key to a sustainable approach to building. And moreover, the historical significance of old structures has become a communicative symbol of cities (Moneo, 2018, p.40) that – today – speak to us (Jencks, 2017) in multiple ways. If "complex adaptive systems" help reinterpret and expand upon such languages, the meanings of existing building parts or fragments transform and take on new contexts. Simultaneously, connections are formed between the past and present creating multiple wholes of rich interrelations.

3. DISJUNCTION

As a design technique, disjunction reveals itself in the interplay between form and function, as well as among different forms. Since the 1970s, it has become a prominent architectural phenomenon, manifesting as the heterogeneous re-presentation of architecture (Tschumi, 1987, p.113). This shift has gradually replaced conventional form-function junctions, redefining the architectural landscape. Postmodern architects have linked diverse functions to familiar forms through Modernist indexical form-function relationships. Following this, formal strategies such as montage, collage, and assemblage emerged from the breakdown of previous meaning systems. Ultimately, disjunctive works formally combine continuity and discontinuity, shaped by edges and boundaries to explore a plural notion of "differences" within a postmodern framework (Hays, 2003, p.13).

An architectural method of 'disjunction' [and] its common denominator

1. Rejection of the notion of 'synthesis' in favour of the idea of dissociation of disjunctive analysis:
2. Rejection of the traditional opposition between use and architectural form, in favour of a superposition of or juxtaposition of two terms that can be independently and similarly subjected to identical methods of architectural analysis:
3. As a method, emphasis would be placed on fragmentation, superimposition theoretical tool for the making of architecture. (Tschumi, 1988, p.35)

From a parallel perspective, in "Reality modelled after images" (2022), Michael Young argues that managing disjunctions—particularly at the seams or borders between forms—is crucial for negotiating diverse perceptions of reality in the realm of digital images and their cultures. He suggests that this control strategically engages users in the dialectics of issues such as morality, politics, and tradition, provoking them to relocate and reconsider their relationship to a world that once felt familiar (p.77–78).

3.1 Architecture of disjunctions: Parc de La Villette

In "Bernard Tschumi, Parc de La Villette, Paris" (1988), Tschumi claims that "The Parc de la Villette (1982–1987) is the largest building of disjunction in the world" (p.33). The park resulted from a 1982 design competition and contains 26 pavilions—10 × 10 × 10 m cubes called "Folies" (p.33)—arranged on a 120 × 120 m^2 point grid within one of Paris's largest parks.

In "Madness and the Combinative, Disjunction" (1984–1991), Tschumi explains that each Folie represents a disjunctioned "fragment" (Tschumi, 1994, p.177–178) of Paris, involved in a process of "transference" (p.177–178) between the city and the site. These fragments are transferred from the city to the site by breaking previously established form-function relationships (Tschumi, 1987, p.112) and then aggregated into Folies. Consequently, the Folies express physical and conceptual disjunctions made up of urban fragments stripped of recognizable functions. A standardized module of steel panels, all painted the same red, softens their defamiliarized appearance, recalling "the British public telephone booth or the Paris Metro gates" (Tschumi, 2003, p.42).

Figure 1: Parc de La Villette, Paris, France. The biggest disjunction project in the world. (Photos: Authors)

3.2 Philosophical context

Through "Manhattan Transcript" (1976–1981), Bernard Tschumi introduces disjunction to architectural discourse by discussing "discontinuity" (p.20). He draws on Michael Foucault's "Order of Things," where the same form can have different meanings in different contexts (p.21). The following year, Tschumi applied disjunction as a design technique in "Parc de La Villette" (1982–1985). After philosopher Jacques Derrida wrote "Point de folie - Maintenant l'architecture" (1986), Tschumi's concept of disjunction became closely linked to Derrida's philosophy of deconstruction and architectural heterogeneity. This connection was solidified through Tschumi's collaborations with Derrida in symposiums and publications.

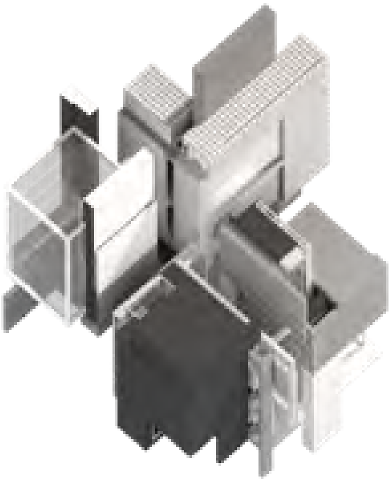
> *trans*- (transcript, transference, etc.) and, above all, *de*- or *dis*-. These words speak of destabilisation, deconstruction, dehiscence and, first of all, dissociation, disjunction,

disruption, difference. An architecture of heterogeneity, interruption, non-coincidence (Derrida, 1986, p.12).

In an etymological sense, disjunction dislocates or disconnects a junction, which means an act of joining from Latin "iungere," or "to join together" (Harper, 2025). Junctions occur where more than two things meet, such as a traffic crossroad, an electronic circuit bifurcation, a cell structure in an organism, or even a restaurant or store as a meeting place. Accordingly, the term junction has been used to indicate a formal composition in order. For example, a junction can mean two lines formally crossing on a ceiling plan: "the centers of two consecutive arcs and their junction" (Durand, 1805; 2000, p.114). It also refers to a formal intersection between architectural elements, such as chimney and roof: "junction with the roof being protected by wide inclined strips" (Viollet-Le--Duc, 1919, p.294).

The semiotic complication that ensues arises from the recognition of forms through their functions. This suggests that a form is comprehended through its practical application or its symbolic meanings derived from social or historical contexts (Gottdiener and Lagopoulos, 1986, p.56). During the 1960s, semiotics scholars such as Umberto Eco investigated the semiotic relationships between form and function. In particular, Eco's seminal work, "Function and Sign: Semiotics of Architecture" (1968) examines the range of form-function relationships from direct to indirect representation. According to Eco (p.63), a junction is denotative when a form clearly expresses its utility or inhabitability. Secondly, a junction is connotative when a form conveys symbolic values from contextual narratives such as society, culture, and history (p.64). Eco emphasizes that the modernist conception of "form follows function" should be understood within the broader framework of semiotics (p.63).

Figure 2: The Country Clubhouse (left) (1973–1974), Oita, Japan. Differences and heterogeneity in form and function are ultimately merged under a single overarching roof.



House X (right) (1975), unbuilt. The design bifurcates from a group of simple boxes intended to be completely unrelated to the world's sign system. This irrelevance pushes the boundary of form into unreadability or disjunction. (Images: Authors)

3.3 Disjunctive synthesis

The discourse of disjunction involves semiotic interpretations of form and function beyond the modernist form-function junction, representing heterogeneous discontinuity (Derrida, 1986). Since "Of Grammatology" (1967), Derrida developed concepts of difference, discontinuity, and disjunction between signifier and signified. This is contrasted by the concept of "heterogeneous discontinuity" (Yatsuka, 1991, p.21).

In "Arata Isozaki after 1980: From Mannerism to the Picturesque" (1991), Hajime Yatsuka explains Isozaki's key idea of "disjunction" (p.21). However, Yatsuka links it to "disjunctive synthesis" (p.21) from "Anti-Oedipus" (1972), by philosophers Gilles Deleuze and Félix Guattari, rather than Derrida's disjunction, though crediting Tschumi's early role.

While the overall design approach is similar, the details differ significantly. Despite sharing the idea of heterogeneity, Isozaki's disjunctive synthesis aims to remove differences or hierarchies in architectural form (p.21). This aligns with the idea of "synthesis" (Tschumi, 1988, p.35), which contrasts with Tschumi's design methods.

> By developing their idea of "disjunctive synthesis", which spawned other concepts like *Rhizome* and *corps sans organs* [body without organs], Deleuze and Guattari have been trying to abolish the idea of organization itself. In the Rhizome model, no distinction is made between the whole and its parts. To illustrate this anti-organization they refer to the Gothic, contrasting it with the classical articulation of parts within the whole (Yatsuka, 1991, p.22).

3.4 Disjunctive imagery

In his 1982 work "House X," Peter Eisenman introduced a design methodology developed from his 1975 project of the same name. At the time, the form-function relationship was regarded as a "constant flux" (p.8), unstable and unpredictable. Rather than resolving this ambiguity, Eisenman created formal languages deliberately distanced from conventional practices.

In the introduction, "From Structure to Subject: The Formation of an Architectural Language" (1982), Mario Gandelsonas explains that House X liberates architectural design from the functionalist dogma of "form follows function" (p.7). Eisenman's approach emphasizes "syntax" (p.8), aiming at overcoming functionalism's arbitrariness and constant change, in which forms are defined by functions of institutional preferences or "individual interpretations" (p.8). Drawing on Chomsky's model of syntax, Eisenman developed a formal language without meaning—a pure grammatical system or "a pure syntactic sign" (p.10)—that generates itself without referring to the external world, opposing structuralism (p.8).

In "Transformations, Decompositions and Critiques: House X" (1982), Eisenman frames this pure syntax work as "a disjunctive imagery" (p.38). This imagery is based on decomposition and transformation of fundamental geometries like the square and L-shape, which Eisenman's glossary defines as having no connection to the world (p. 38). He argues that the new harmony of House X derives from its "built-in geometric unity" (p.76), rather than any recognizable worldly figures, resulting in its "architectonic distinctiveness" (p.76).

4. STUDIO EXPERIMENTAL DESIGN

The research paper employs the design techniques of disjunction in a master design studio course at Wuppertal University in Germany. The Studio Experimental Design employs a research-based design methodology, albeit without any assurance of physical construction. Consequently, the outcomes of the course remain within the domain of academia. However, it also aspires to critically engage with contemporary architectural practices by referencing existing built projects and employing a range of digital design tools for representation. The paper selectively introduces two design results by Anton von der Heyden and Luca David Hager.

The course commences with the meticulous digital modeling of reference buildings in three dimensions. This digital reconstruction endeavors to represent a building form with sufficient precision to extract a design concept and its formal languages. Concurrently, site visits or literature studies are conducted to augment the conceptual reading of the references. The course frequently assigns participants to integrate their formal languages in a design project. Ultimately, individual participants create a virtual diorama constructed exclusively by the extracted formal languages.

4.1 Atrium junctions

In 2024, the Studio Experimental Design focused on "(dis-)junction," thematically framing atrium construction by emphasizing their formal qualities and importance as architectural elements. These junctions act as meeting places that facilitate interaction and exchange. Formal junctions between architectural elements—such as between column and floor, floor and wall, or floor and stairway—are revealed through buildings.

Herman Hertzberger's Centraal Beheer, built in 1972, and Peter Behrens's Höchst AG Office (Peter Behrensbau), constructed in 1924, demonstrate different qualities of junction in the forms of atrium. Centraal Beheer shows a series of junctional atriums located between and within box volumes, serving to collect and distribute building elements while functioning as communal meeting points. These junctions evoke a sense of visual continuity, as if in enfilade, despite the lack of direct visual evidence in different axes. In contrast, Höchst AG's office has a distinctive centralized junction within groups of homogeneous office rooms. This singular big void junction combines structural, formal, and patterned elements to create a rich spatial experience.

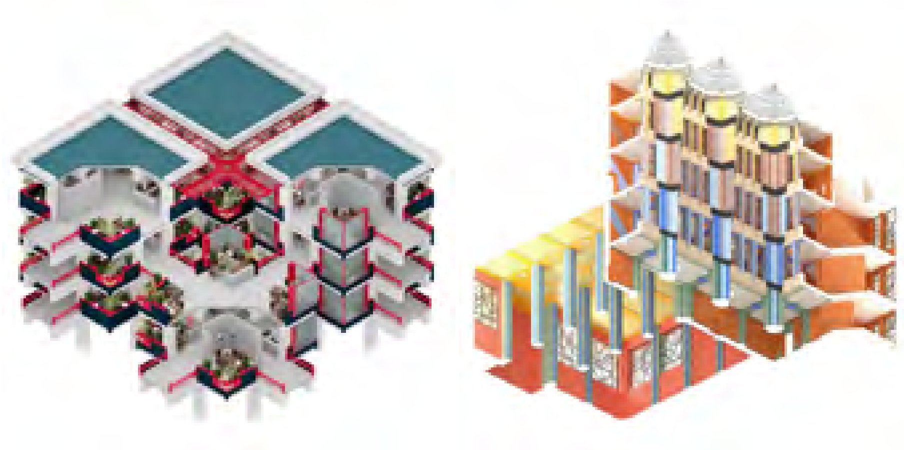


Figure 3: Partial atrium models of Centraal Beheer (left), Apeldoorn, Netherlands (1972) and Höchst AG (right) (1924). (Images: Authors)

4.2 Representation: Unfold drawings

It became evident that conventional drawings, such as plans, sections, and elevations, were inadequate for accurately representing the true atmosphere. Despite the integration of these elements, residual disjunctions persist within the drawings, precluding the complete representation of spatial phenomena. For instance, the spatial depth and sequence are reduced in a flat view, which leaves visible gaps where the columns are supposed to be. Therefore, there are instances of accidental poche figures in which columns or walls are present. In both cases, spatial continuity or layers cannot be expressed.

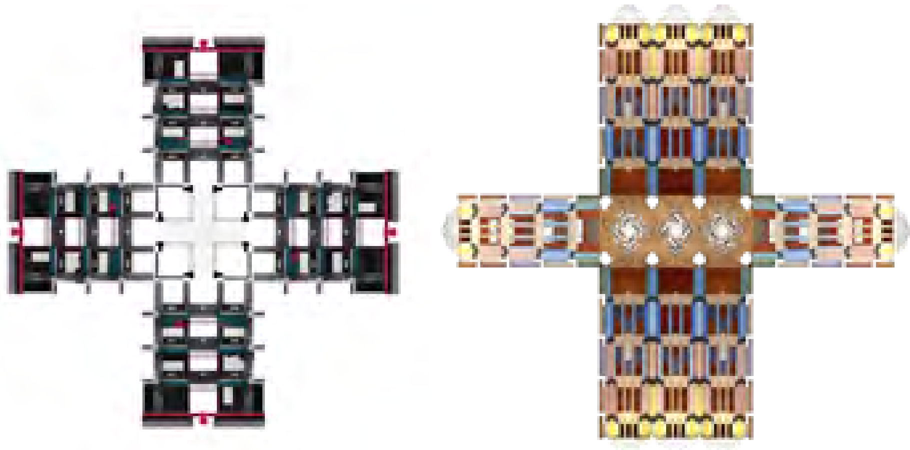


Figure 4: Unfold drawings of the atriums from Centraal Beheer (left) and Höchst AG (right). (Images: Authors)

4.3 Representation: Speculative unfold drawings

Each project was guided to produce real spatial representations, which were then thematically modified according to their concepts. The Centraal Beheer atrium exemplifies spatial sequence through the extension and overlap of atrium elevations at the corners. Notably, the articulated superimpositions integrate seamlessly into the original structure, preserving its integrity. This is because the formal language uses modular units applied throughout the building, allowing it to adapt to new modifications in configuration. The spatial depth and layering of Höchst AG's atrium result from stretching disconnected parts and filling the poche in plan. During reconnections, the drawing creates another pocket in the section, triggering a chain reaction. Despite reconnecting the disjunction between floor and columns, the gallery corridors open as new pockets.

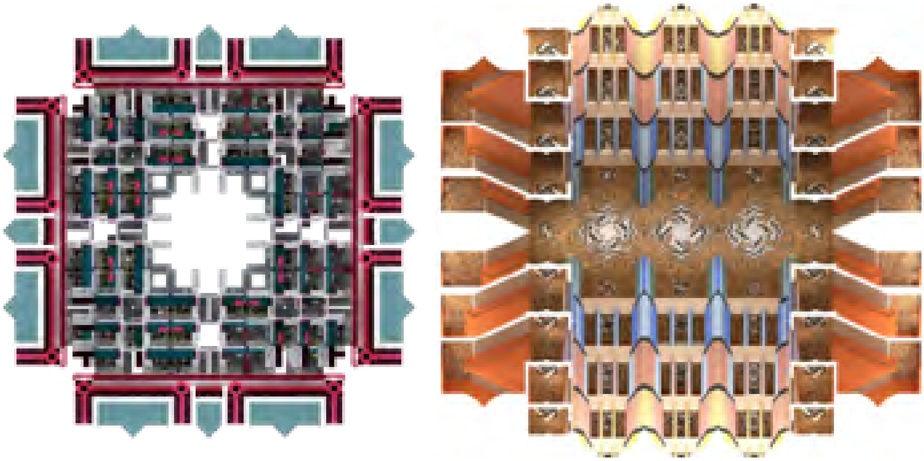


Figure 5: Unfolded drawings of the atriums from Centraal Beheer (left) and Höchst AG (right). (Images: Authors)

4.4 Formal language study-1: Minimum units of form

The analytic model of unit-study is crucial to understand the detail edge conditions of formal languages. The Centraal Beheer's language is composed of multiple variations of singular components, which respond to different contextual conditions by altering their orientation and assembly sequences. In contrast, the Höchst AG's language bifurcates from the floor patterns as a field of fragmented grid. They turn into columns and wall patterns that produce different poche figures in drawing representations.

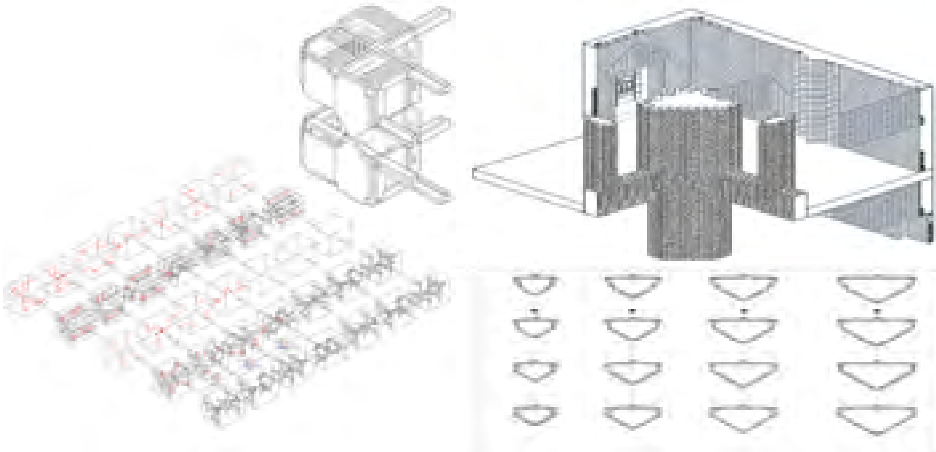


Figure 6: Minimum unit study of Centraal Beheer (left) and Höchst AG (right). (Images: Authors)

Formal language study-2: Fragments

Based on the extracted formal languages, each student developed their formal language of disjunction. For instance, the tensions between continuity and discontinuity are found from the different assemblies of the same structure in Centraal Beheer. Similar tensions are recognized from the figure-ground condition around poches in Höchst AG. Centraal Beheer's language relies on an additive assemblage that the fragments consist of rule-based compositions. The regular unitary compositions exhibit variability in their edge conditions by either continuing or discontinuing the same structure in diverse directions. Conversely, Höchst AG's approach involves the extraction of components from a part-to-the-whole relationship. The poche fragments result in the rendering of three-dimensional forms that ironically locked up in a two-dimension. This style of rendering has the effect of confining the boundaries of fragments to the background.

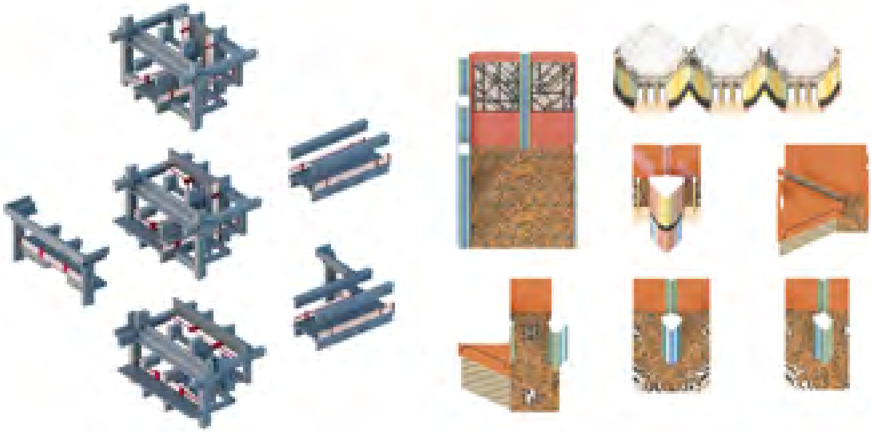


Figure 7: Fragment compositions of Centraal Beheer (left) and Höchst AG (right). (Images: Authors)

4.6 Assemblage in diorama

The method of assembly was approached differently. On the one hand, Centraal Beheer's language focused on controlling the connection and disconnection of interior spaces. On the other hand, Peter Behrens's language was deformed into a fixed view of perfect axonometry to represent the negotiation between figure and ground in a two-dimensional graphical space. The recomposition of Centraal Beheer's fragments is situated in a virtual urban setting that negotiates connectivity both within and beyond the architectural form, while Höchst AG's fragments are aggregated and flattened into a 2d graphical space that blurs the boundary between figure and ground through poche. These two projects express distinct spatial qualities through the familiar and historical language of architecture. The narratives of the original buildings linger in every corner of the new design, constructing a heterogeneous environment imbued with cognitive familiarity. Various conditions of disjunction are explored by manipulating the boundary conditions between fragments.

Figure 8: The virtual urban diorama of Centraal Beheer's formal language (left) and the 2.5-dimensional figure-ground space of Höchst AG (right). (Images: Authors)

5. CONCLUSION

This study looks at adaptive reuse through the lens of a technique called disjunction. The ways that architectural forms are put together in new settings challenge the traditional connection between form and function. Disjunction operates as both a critical and design strategy that offer ways to bind diverse architectural languages across history.

Digital modeling plays a vital role in this process, not only for visualizing spatial arrangements but also as a tool for critical inquiry. It enhances the capacity for imagination and spatial analysis, enabling architects to move forward from passive responses to the built environment as preservation purposes. It confronts contemporary challenges such as sustainability. As architectural practice increasingly emphasizes resource conservation and long-term adaptability, the techniques of disjunction speculate the meaning of sustainability in cultural, social, and historical dimensions.

The speculative aspects of disjunction carry on architectural expressions of heterogeneity from postmodern discourse in architecture. Accordingly, the relevant study of architectural semiotics and deconstructivism follows the heterogeneous ideology which coincide with the fictional applications of spolia and fragmentation over the architectural conservation in the 21st century. It is eventually, a strategy of "both and" rather than "either or" that has been inherited from the postmodernist lesson of heterogeneity.

I prefer "both-and" to "either-or," black and white, and sometimes gray, to black or white. A valid architecture evokes many levels of meaning and combinations of focus: its space and its elements become readable and workable in several ways at once (Venturi, 1966, p.16).

REFERENCES

Derrida, J. (1986) Point de folie – Maintenant l'architecture, Éditions Galilée, Paris.

Durand, J.-N.-L. (2000) Précis of the Lectures on Architecture: With Graphic Portion of the Lectures on Architecture, Getty Research Institute, Los Angeles, CA.

Eco, U. (1986 [1968]) "Function and Sign: Semiotics of Architecture", in Gottdiener, M. and Lagopoulos, A.P. (eds.) The City and the Sign: An Introduction to Urban Semiotics, Columbia University Press, New York, pp. 55–86.

Eisenman, P. (1982) House X, Rizzoli, New York.

Gandelsonas, M. (1982) "From Structure to Subject: The Formation of an Architectural Language", in Eisenman, P. House X, Rizzoli, New York, pp. 7–31.

Goffi, F. (2016) “Built Conservation and the Unfinished Fabrics of Time”, Architectural Design, Vol. 86, No. 1, pp 24–33.
Gönül, H. (2023) “Contemporary Spolia: Afterlives of Ruins in Fragments”, Studies in History and Theory of Architecture, No. 11, pp. 157–174.
Gottdiener, M. and Lagopoulos, A.P. (eds.) (1986) The City and the Sign: An Introduction to Urban Semiotics, Columbia University Press, New York.
Harper, D. (n.d.) Junction. Online Etymology Dictionary. Retrieved June 25, 2025, from https://www.etymonline.com/word/junction
Hays, M.K. (2003) “The Autonomy Effect”, in Tschumi, B. Bernard Tschumi, Universe Publishing, New York, pp. 7–16.
Jencks, C. (2011) The Story of Post-Modernism: Five Decades of the Ironic, Iconic and Critical in Architecture, John Wiley & Sons, London.
Jones, P.B. (2002) “Municipal Entente: Town Hall, Utrecht”, ARQ, Vol. 5, No. 4 (October), pp 46–53.
Kipnis, J. (1993) “Toward a New Architecture”, Architectural Design, Vol. 63, No. 5, pp 16–23.
Moneo, R. (2018) “Seeking the Significance of Today’s Architecture”, Log, No. 44, Fall, Anyone Corporation, pp. 35–44. Paper delivered at the inaugural Soane Annual Lecture, November 2017.
Olgiati, V. and Breitschmid, M. (2019) Non-Referential Architecture, Park Books, Zurich.
Rabaça, A. (2023) “Spolia and the Open Work”, Architecture Theory Journal (Footprint), Vol. 16, No. 2, pp 41–66.
Salingaros, N.A. (2004) Anti-Architecture and Deconstruction, Umbau-Verlag, Solingen, Germany.
Tschumi, B. (1976–1981) “Manhattan Transcript”, Oppositions, Nos. 8–17.
Tschumi, B. (1988) “Bernard Tschumi, Parc de La Villette, Paris”, Architectural Design, Vol. 58, No. 11–12, pp. 40–47.
Tschumi, B. (1996) Architecture and Disjunction, MIT Press, Cambridge, MA.
Tschumi, B. (2003) Bernard Tschumi, Universe Publishing, New York.

Venturi, R. (1966) *Complexity and Contradiction in Architecture*, Museum of Modern Art, New York.

Viollet-le-Duc, E.-E. (1919) Rational Dictionary of French Architecture from the 11th to the 16th Century, translated by N. Clifford Ricker, University of Illinois, Champaign.

Yatsuka, H. (1991) "Arata Isozaki after 1980: From Mannerism to the Picturesque", in Koshalek, R. (ed.) Arata Isozaki: Architecture 1960–1990, Museum of Contemporary Art, Los Angeles / Rizzoli, New York, pp. 18–23.

Young, M. (2021) Reality Modeled After Images: Architecture and Aesthetics after the Digital Image, Routledge, New York.

A REVIEW OF CLAY AND ALGINATE BIO-COMPOSITES: MATERIALS, FABRICATION, AND APPLICATIONS IN SUSTAINABLE ARCHITECTURE

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ABSTRACT:

As the construction industry remains one of the largest consumers of raw materials and energy, addressing its environmental footprint is critical to achieving global sustainability goals. A significant contributor to this impact is the widespread use of petroleum-based insulation materials, which are non-renewable, energyintensive to manufacture, and difficult to dispose of sustainably. These materials pose long-term risks to ecosystems, human health, and waste management systems. In response,

growing attention is being directed toward natural, renewable, and biodegradable alternatives for thermal insulation—particularly those compatible with digital fabrication techniques such as 3D printing.

This article provides a comprehensive review of current research on clay–alginate composites, synthesizing findings from material science, architecture, and additive manufacturing to evaluate their potential as bio-based thermal insulation systems. Clay is a naturally occurring, abundant material that has been used in construction for centuries due to its thermal stability, availability, and structural properties. Recent developments in clay-polymer composites have enhanced its mechanical and thermal behaviour, broadening its application in contemporary sustainable architecture. Its plasticity and rheological behaviour also make clay a strong candidate for extrusionbased additive manufacturing.

Alginate, a polysaccharide derived from brown seaweed, is widely recognized for its biodegradability, renewability, and non-toxicity. While it has found extensive use in the biomedical and food industries, its potential in construction remains under-explored. When cross-linked with divalent cations like calcium (Ca^{2+}), alginate forms stable hydrogels, making it a promising additive in composite materials. Its success in bioprinting suggests high potential for sustainable 3D printing applications in the building industry.

By combining the structural strength and thermal mass of clay with the gel-forming, biodegradable properties of alginate, these composites represent a promising direction for future research. This paper synthesizes current literature on both materials, reviews emerging trends in sustainable insulation, and identifies key research gaps related to performance evaluation, scalability, and integration with digital construction technologies.

Keywords: alginate, biopolymers, clay, minerals, insulation materials, 3D printing

1. Introduction

The environmental impact of the construction industry is a growing global concern ((UNEP), 2022). As one of the largest consumers of raw materials and energy, the sector accounts for a significant share of global carbon emissions and resource depletion. A major contributor to this impact is the use of conventional insulation materials— such as polystyrene, polyurethane, and mineral wool—which are fossil-based, non-recyclable, and often toxic across their lifecycle.

Despite their widespread use and thermal performance, these materials present serious limitations. They contribute to waste generation, harmful emissions, and poor indoor air quality. Moreover, most commercially available options remain difficult to recycle and pose environmental and health risks throughout their use and disposal phases. Although demand for greener solutions is increasing—particularly in alignment with the Sustainable Development Goals (United Nations Environment Programme, 2024-02)—the construction industry has been slow to embrace alternatives. Conventional practices continue to dominate, underscoring the urgent need for innovative, sustainable materials.

In this context, clay–alginate composites offer a promising alternative. Combining mineral and biopolymer components, they present an environmentally friendly and potentially scalable solution. Clay contributes thermal mass, structural stability, and compatibility with digital fabrication, while alginate—a biodegradable polysaccharide— enables gelation and ionic cross-linking, forming lightweight, porous, and resilient foam structures. These properties make clay–alginate systems well-suited for next-generation insulation applications.

This review examines the current state of research on clay–alginate composites for building insulation. It explores their chemical and structural characteristics, fabrication techniques, and integration into 3D printing workflows. Positioned within the broader landscape of insulation technologies, these materials are evaluated for their functional performance and environmental impact. By synthesizing insights from architecture, materials science, and sustainability, this work identifies research gaps and supports the development of bio-based insulation aligned with circular construction principles.

2. STRUCTURE OF THE REVIEW

This paper is structured to provide a comprehensive overview clay–alginate composites in the context of sustainable insulation materials and additive manufacturing. It begins with a detailed examination of the two core materials—clay and alginate—highlighting their geological and biological origins, chemical compositions, and material properties relevant to construction. The discussion then moves to 3D printing techniques, emphasizing their compatibility with natural composite materials. Following this, the applications section explores the role of these materials as thermal insulation in buildings, considering both environmental and technical performance.

2.1. Materials

2.1.1. *Clay*

Clay has been a fundamental building material for millennia, valued for its abundance, durability, and thermal mass in traditional construction (Houben & Guillaud, 1992; Marsh & Kulshreshtha, 2022). With increasing environmental awareness, clay presents a sustainable alternative due to its low-energy processing, recyclability, and availability, requiring less processing than concrete or steel (Huarachi et al., 2020; Mateus et al., 2020).

Clay is formed through the weathering and decomposition of feldspar and other silicate minerals. Feldspar itself is composed of aluminium oxide, silicon dioxide, and a secondary metal oxide such as potassium, sodium, or calcium. The primary clay minerals are *kaolinite* and *montmorillonite*, with *illite* occurring to a lesser extent (Kumari & Mohan, 2021). Figure 1 shows the structural differences between the clay minerals *kaolinite*, illite, and *montmorillonite*. *Kaolinite* has a simple layer structure, where each aluminum hydroxide layer is closely connected to a silicon oxide layer. This tight structure leads to a low ion-binding capacity. *Illite* has a more open structure with potassium ions between the layers, allowing for limited ion exchange. *montmorillonite*, in contrast, has a flexible layer structure with water and exchangeable cations in between, which enables a high ion-binding capacity and the ability to swell. Because each aluminum layer in *montmorillonite* is surrounded by two silicon layers, it can bind more ions than *kaolinite* (Minke, 2006). They exhibit high cation (e.g., Ca^{2+}) exchange capacity facilitating interactions with negatively charged additives (e.g., alginate), which can improve composite strength and performance (da Silva Fernandes et al., 2018).

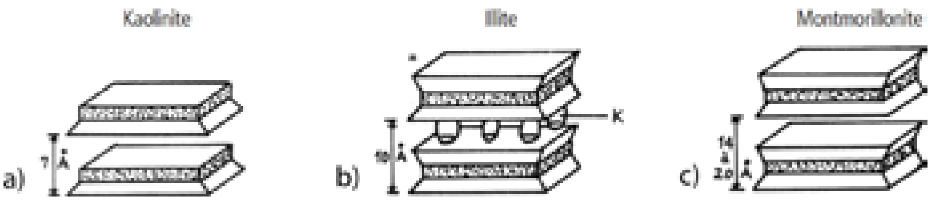

Figure 1: Structure of the three most common clay minerals, based on Houben and Guillaud (Houben & Guillaud, 1992).

While traditional applications persist, advancements in materials science have expanded clay's role, including claypolymer nanocomposites that enhance strength, durability, and thermal insulation (Galán-Marín et al., 2010a; Ni et al., 2022). Additionally, 3D printing enables the creation of complex geometries and custom structures, further integrating clay into modern architecture (Wolf et al., 2022). These innovations continue to broaden clay's potential in load-bearing structures, facades, and interior finishes (Del et al., 2024; Shubbar et al., 2019). Additionally clay foams have gained significant attention for their porous structures, which enhance mechanical flexibility and durability. Minas et al. highlight the potential of recyclable clay foams as energy-efficient, cost-effective insulators (Minas et al., 2019). Additionally, Lagzdiņš et al. demonstrate that incorporating clay platelets into polymer foams improves tensile strength and compressive resilience, further enhancing material durability (Chen et al., 2025; Lagzdiņš et al., 2022). Beyond mechanical benefits, clay foams also exhibit exceptional thermal stability, particularly with *kaolinite* and feldspar, which increase decomposition temperatures and enhance fire resistance (Agrawal et al., 2019; Vijayan et al., 2020). Palen et al. further demonstrate that specialized clay-based coatings significantly reduce flammability while maintaining foam integrity under heat exposure (Palen et al., 2021). Overall, integrating clay into foam structures enhances both mechanical properties and thermal performance, positioning these materials as promising candidates for sustainable insulation and protective applications.

2.1.2. *Alginate*

The integration of biopolymers such as starch, lignin, and chitosan into insulation materials has become a key focus in sustainable materials research. Among biopolymers, alginate, derived from brown seaweed, has demonstrated significant potential as a bio-based binder in mineral matrices, particularly in the development of clay foams alginate and fibres (Zdiri et al., 2022; Zia et al., 2020). These eco-friendly alternative to synthetic polymers can enhance the mechanical strength and thermal performance of insulation composites while offering biodegradability and a lower environmental footprint (Hurtado et al., 2022; Nazrun et al., 2024; TG et al., 2023).

Alginate is a polysaccharide derived from algae, specified brown seaweed. Algae are marine fast-growing photosynthetic species and are categorised to macroalgae and microalgae depending on their size (Singh & Saxena, 2015). Marine macroalgae, commonly known as seaweed, attach themselves to rocks or other coastal substrates and represent the marine equivalent of terrestrial plants. They vary in form from minute filamentous species to giant kelps that can grow up to 70 meters in length and inhabit depths of up to 200 meters. Through photosynthesis, algae contribute to more than 50% of global oxygen production and function as natural solar converters, capable of synthesizing a wide range of valuable compounds (Suganya et al., 2016).

The distribution of brown seaweed species varies globally. The primary genera used for alginate extraction include *Laminaria*, *Saccharina*, *Ecklonia*, *Macrocystis*, *Lessonia*, *Ascophyllum*, *Nereocystis*, and *Durvillaea*. The figure 2 illustrates five of these genera, demonstrating their global abundance (Eger et al., 2023). Depending on the species, up to 40% of sodium alignate can be extracted from the dry weight of brown seaweed (Abka-Khajouei et al., 2022).

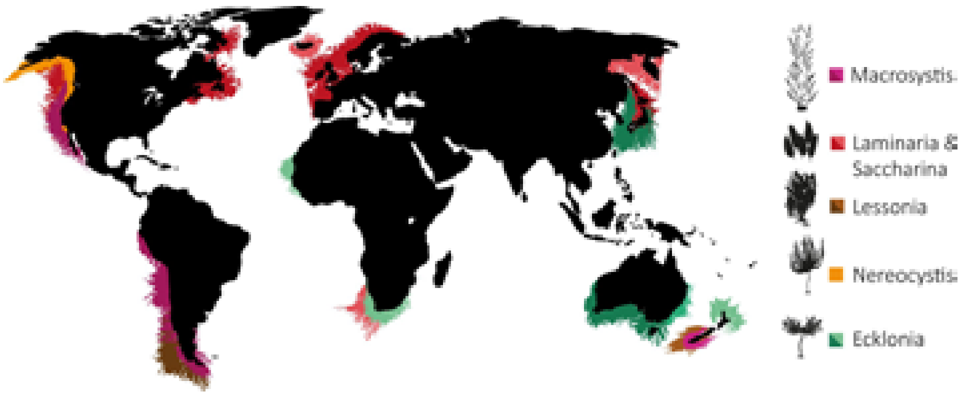

Figure 2: Global distribution of key brown seaweed genera used in alginate production. The map illustrates the regional abundance of five economically significant genera: *Macrocystis*, *Laminaria* & *Saccharina*, *Lessonia*, *Nereocystis*, and *Ecklonia*.

The cell walls of brown algae differ from those of land plants and other algae in that they contain significantly less cellulose (Table 1). This reduced cellulose content, combined with the presence of flexible polysaccharides like alginate, allows brown algae to remain resilient and adaptable in dynamic aquatic environments, such as under wave action and tidal forces. The main components of these cell walls are sulphated fucans and alginates, each about 40% of the walls content, along with proteins, specific sugars, phlorotannins (polymers), and iodine (Michel et al., 2010; Rabillé et al., 2019). It has to be noted that the exact composition varies considerably between species, developmental stages, and environmental conditions, and reported percentages are only approximate (Synytsya et al., 2015).

Table 1: Approximate composition and functional roles of brown seaweed cell wall components according to *Michel et al.* (Michel et al., 2010).

Component	Approx. [%]	Main sugar	Function
Alginate	~ 30–40 %	Mannuronic, Guluronic	Gel formation, flexibility
Fucoidan	~ 10–15 %	Fucose	Flexibility, water retention, protection
Cellulose	~ 7–10 %	Glucose	Strength, structure
Hemicellulose	~ 5–10 %	Glucose	Wall support, matrix
Proteins	~ 5 %	–	Structure, enzymes
Phlorotannins	~ 5–10 %	–	Cross-linking, protection
Inorganic (e.g. iodine)	up to ~ 5 %	–	Defence, stress response

As previously mentioned, proteins are a component of brown seaweed cell walls and play a crucial role in the biosynthesis of alginate. The protein *AlgG* is an enzyme which is involved in the modification of the alginate polymerization. Figure 3 shows the layout of the biosynthetic operons, with genes colour-coded based on their roles in the biosynthesis process. The pathway of alginate biosynthesis is generally divided into (i) production of the activated sugar nucleotide precursor, (ii) polymerization and transport across the inner membrane, (iii) postpolymer modification of the polymer in, and passage through the periplasm, and (iv) export from the cell. Each of these proteins is part of the biosynthetic complex, and if this complex doesn't form, the polymer gets exposed to AlgL and is broken down (Franklin et al., 2011).

The cell wall has two main components: (1) fibrils—long, thread-like structures composed of polysaccharides such as cellulose and mannans that form the primary framework—and (2) an amorphous matrix—a gel-like substance in the periplasmic space where alginic acid and fucoidan are synthesized (Figure 3)(Davis et al., 2003; Karaduman et al., 2022).

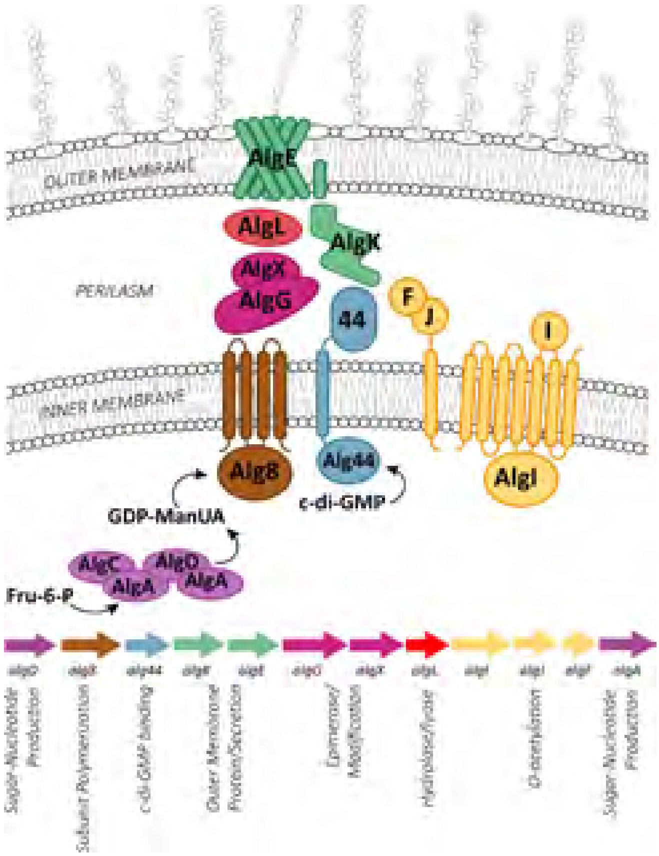

Figure 3: Proposed architecture of the alginate biosynthetic complex. Proteins are colour-coded based on their proposed functions as illustrated (Franklin et al., 2011).

=Following the overview of alginate biosynthesis, it is important to examine its chemical composition and properties, as these play a crucial role in its cross-linking behaviour and functional performance. Alginate is a linear anionic polysaccharide, composed of α-L-guluronic acid (G) and β-D-mannuronic acid (M) blocks linked by 1,4glycosidic bonds. These acid residue blocks can be homogenously (MM or GG) or heterogenously

(GM or MG) arranged in various G/M ratios, resulting in different alginate structures and properties (Houben & Guillaud, 1992). The G-blocks of alginate are predominantly responsible for intermolecular cross-linking with divalent cations such as Ca^{2+}, forming a three-dimensional hydrogel network via the ”egg-box” structure (Figure 4). Increasing the concentration of Ca^{2+} generally enhances gel strength by promoting additional cross-links between G-blocks, thereby improving the rigidity and mechanical stability of the gel (Abka-khajouei et al., 2022; Bojorges et al., 2023; Fischer & Dörfel, 1955; Lee & Mooney, 2012).

Figure 4: Chemical structure of alginate, forming a 3D network and the resulting “egg--box” model structure with calcium-linked junctions (Bojorges et al., 2023).

2.1.3. *Composite*

Alginate has attracted attention for its biodegradability, renewability, non-toxicity, and biocompatibility, and is therefore used in various industries(Hurtado et al., 2022; Wawszczak et al., 2024). Alginate can be used as a matrix for composites to which reinforcements can be added in various forms, resulting in improved physical and mechanical properties (Avila-Ramirez et al., 2021; Gady et al., 2016; Kyaw Oo D’Amore et al., 2017).

Alginate composite materials are produced by addition of reinforcements into alginate matrix, to improve a range of physical and mechanical properties like mechanical strength, thermal stability, and enhanced compatibility (Dove et al., 2016). Reinforcements agents include particles crop, bioceramics (Galán-Marín et al., 2010b), fibers (Karaduman et al., 2022; Lacoste et al., 2018) and crop by-products (Palumbo et al., 2017, 2018). The composites produced in this way are interesting for construction and building fields, especially when used for insulation, as well as considering the global trend of developing eco-friendly or bio-based composite materials in this areas.

The general aim is to produce elastic materials with insulating and flame retardant properties that match those of existing commercial alternatives. Studies indicate that alginate significantly improves the elasticity and structural integrity of clay-alginate composites, making them highly suitable for insulation applications (Zhu et al., 2022). Cruz et al. demonstrated that alginate aerogels exhibit excellent thermal insulation properties while maintaining the flexibility required for construction use (De la Cruz et al., 2024; Fan et al., 2022).

2.2. Applications

2.2.1. *Insulation Material*

In the European market, insulation materials fall into two main categories: inorganic fibrous materials (glass and rock wool) and organic foams (EPS, XPS, PUR-PIR) (Villasmil et al., 2019). Beyond market classifications, they can be grouped into three categories based on composition and environmental impact (Schiavoni et al., 2016).

Conventional insulation materials such as PUR-PIR, EPS, XPS, mineral wool, and fibreglass have been industry standards for decades due to their effective thermal performance and cost efficiency. Petroleum-based foams offer low thermal conductivity and energy loss (Abu-Jdayil et al., 2019; Jelle, 2011). ArmaFlex®, a product in the construction industry, is known for its flexibility, allowing easy installation around pipes, ducts, and complex shapes while minimizing gaps and thermal bridges. Additionally, it offers properties like superior thermal insulation, high moisture resistance, durability and fire safety. However, these materials are non--biodegradable, can emit volatile organic compounds (VOCs), and can not be recycled, due to insoluble joining with the construction, raising concerns about environmental impact and indoor air quality. Similarly, mineral wool and fibreglass provide strong thermal and acoustic insulation but require energy-intensive production and pose handling risks due to brittleness and synthetic binders.

Alternative insulation materials include natural fibres like wool, hemp, cotton, and straw, etc.(b6.b7; Abu-Jdayil et al., 2019) which offer biodegradable and sustainable solutions with lower embodied energy (Veeraprabahar et al., 2022). These materials offer environmentally friendly and sustainable alternatives to conventional insulation, with the added benefits of biodegradability and lower environmental impact (Rabbat et al., 2022; Raja et al., 2023). However, they tend to absorb moisture and often require chemical treatments for durability and fire resistance. Additionally, emerging bio-based foams made from starch, lignin, and cellulose reduce fossil fuel dependence but remain mechanically fragile, limiting their use in structural applications (Asdrubali et al., 2015).

Advanced insulation materials such as aerogels and vacuum insulation panels (VIPs) push the boundaries of thermal efficiency but face significant drawbacks (Jin et al., 2020; Volschenk et al., 2024; Wang et al., 2020). Aerogels have extremely low thermal conductivity (Koebel et al., 2012), but are costly and energy-intensive to produce, making large-scale use impractical. VIPs provide exceptional insulation by sealing a porous core in a gas-tight barrier but suffer from high costs, fragility, and limited adaptability in construction (Mao et al., 2020).

These limitations highlight a critical need for a novel insulation material that balances high thermal performance with cost-effectiveness, durable performance, and ease of integration into building practices. Our proposed clayalginate composite material aims to address these challenges by providing a sustainable, bio-based alternative with elastic properties and inherent thermal resistance.

2.3. Techniques

2.3.1. *3D Printing*

The integration of alginate and clay in 3D printing technologies has gained increasing attention, primarily within biomedical research, where these materials have demonstrated synergistic benefits in the development of highperformance bioinks. Alginate, a biopolymer extracted from brown seaweed, is highly valued for its biocompatibility, biodegradability, and hydrogel-forming capability upon cross-linking with divalent cations like calcium. This unique gelation behavior provides structural stability and flexibility—key properties for extrusion-based fabrication processes (Bendtsen et al., 2017). For example, Liu et al. showed that alginate–chitosan hydrogels achieve comparable mechanical strength to other hydrogel systems, confirming alginate's suitability for robust scaffold formation (Q. Liu et al., 2018).

The incorporation of clay, particularly layered silicates such as montmorillonite, significantly improves the mechanical and rheological performance of alginate hydrogels. Clay acts as a natural rheology modifier, enhancing the shear-thinning behavior and structural fidelity required during the printing process (Leu Alexa et al., 2021). This results in nanocomposite hydrogels that are not only mechanically reinforced but also capable of maintaining intricate forms under load—an essential criterion for functional and stable printed components.

Moreover, studies have confirmed that clay–alginate composites demonstrate favorable viscoelastic properties, which are crucial for maintaining layer-by-layer integrity during extrusion-based additive manufacturing. Bilici et al. and Ahlfeld et al. further demonstrated how composite formulations involving alginate and secondary polymers or fillers—such as methylcellulose—can be fine-tuned to improve viscosity, print resolution, and overall material performance (Ahlfeld et al., 2017; Bilici et al., 2023). Rheological control, particularly the balance between flow under pressure and structural recovery post-extrusion, is essential not only for biological applications but equally relevant for architectural use.

Printability is governed by a delicate balance between viscosity and shear-thinning behavior, which dictates how the material flows through the nozzle and stabilizes post-deposition. Wu et al. highlighted that maintaining shear stress below critical thresholds is essential to preserving cell viability during printing. Their findings underscore the importance of controlled degradation and optimized rheology in achieving functional 3D-printed constructs (Wu et al., 2016). Similarly, Liu et al. examined the influence of various clay types on the rheological properties of alginate-based inks, demonstrating that tailored formulations can greatly improve printing outcomes (S. Liu et al., 2017).

While the majority of studies on clay–alginate composites have emerged from biomedical research, the core material properties identified—such as biocompatibility, tunable rheology, and high shape fidelity—are equally valuable in architectural applications. In contrast to conventional casting methods, extrusion-based 3D printing enables the fabrication of geometrically complex and customized insulation elements that can adapt to irregular surfaces and reduce thermal bridging. The additive nature of 3D printing also minimizes material waste and supports the integration of controlled porosity and gradient structures, which are critical for optimizing thermal insulation performance.

In this context, the integration of clay and alginate within digital fabrication workflows represents a promising strategy for developing next-generation insulation materials. Their renewability, environmental compatibility, and excellent printability offer a scalable pathway toward flexible, high-performance components tailored for sustainable and resource-efficient construction.

3. CONCLUSION

This paper has explored the potential of clay–alginate composites as a new class of sustainable and flexible insulation materials for the building industry. Clay, a geologically abundant and historically significant construction material, brings thermal mass, fire resistance, and structural integrity. Alginate, a polysaccharide derived from brown seaweed, offers exceptional flexibility, biodegradability, and hydrogel-forming properties when cross-linked with divalent cations. Together, these materials form elastic bio-foams that present a promising alternative to conventional insulation systems.

Current insulation materials are dominated by fossil-based foams such as polystyrene, polyurethane, and mineral wool. While effective in thermal performance, these materials are non-renewable, energy-intensive, and environmentally problematic throughout their lifecycle. Although bio-based solutions are emerging, most research and commercial efforts focus on rigid or fibrous materials, leaving a significant research gap in elastic, flexible biopolymer foams. This under-representation is critical, especially for applications requiring adaptable, conformal, or geometrically complex insulation systems.

By introducing clay–alginate foams into the discourse, this study addresses both ecological and performancerelated concerns. These composites not only reduce dependence on fossil-derived components but also provide tunable mechanical and thermal properties. Most importantly, their compatibility with additive manufacturing, particularly extrusion--based 3D printing, opens new avenues for digital construction. 3D printing allows for customizable geometries, efficient material use, and integration into prefabricated or complex architectural components—all key factors for sustainable and scalable innovation in the built environment.

The convergence of natural materials with digital fabrication technologies represents a forward-looking strategy for the development of next-generation insulation systems. Clay–alginate foams offer a unique opportunity to rethink how we insulate buildings: with materials that are not only high-performing but also renewable, adaptable, and suitable for circular construction practices.

4. OUTLOOK

Despite increasing efforts to reduce the environmental impact of the construction industry, the development of flexible, sustainable foam insulation materials remains an under-explored area of research. Most bio-based insulation alternatives focus on rigid or fibrous formats, while the market for flexible solutions continues to be dominated by petroleum-derived foams. This represents a critical gap—especially given the importance of adaptable materials in retrofitting, prefabrication, and complex geometrical applications.

However, the translation of these composites from laboratory-scale materials to building-integrated solutions presents multiple challenges. To advance this emerging field, future research should focus on the following key questions:

- In what ways do various clay minerals (e.g., kaolinite versus montmorillonite) influence the mechanical strength, thermal performance, and fire resistance of the composite material?

- What is the long-term performance and durability of clay–alginate foams when exposed to environmental conditions such as humidity, thermal cycling, and microbial activity?
- How does the degree of alginate cross-linking affect the elasticity, structural stability, and thermal conductivity of the composite?
- What rheological behaviour and drying dynamics are necessary to enable effective extrusion-based 3D printing of clay–alginate mixtures at architectural scales?

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REFERENCES

Abka-Khajouei, R., Tounsi, L., Shahabi, N., Patel, A. K., Abdelkafi, S., & Michaud, P. (2022). Structures, properties and applications of alginates. *Marine drugs*, *20*(6), 364. https://doi.org/10.3390/md20060364

Abka-khajouei, R., Tounsi, L., Shahabi, N., Patel, A. K., Abdelkafi, S., & Michaud, P. (2022). Structures, properties and applications of alginates. *Marine Drugs*, *20*(6). https://doi.org/10.3390/md20060364

Abu-Jdayil, B., Mourad, A.-H., Hittini, W., Hassan, M., & Hameedi, S. (2019). Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Construction and Building Materials*, *214*, 709–735. https://doi.org/10.1016/j.conbuildmat.2019.04.102

Agrawal, A., Kaur, R., & Walia, R. S. (2019). Investigation on flammability of rigid polyurethane foam-mineral fillers composite. *Fire and Materials*, *43*(8), 917–927. https://onlinelibrary.wiley.com/doi/10.1002/fam.2751

Ahlfeld, T., Cidonio, G., Kilian, D., Duin, S., Akkineni, A., Dawson, J., Yang, S., Lode, A., Oreffo, R., & Gelinsky, M. (2017). Development of a clay based bioink for 3d cell printing for skeletal application. *Biofabrication*, *9*(3), 034103. https://iopscience.iop.org/article/10.1088/1758-5090/aa7e96

Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, *4*, 1–17. https://doi.org/10.1016/j.susmat.2015.05. 002

Avila-Ramirez, A., Catzim-Ríos, K., Guerrero-Beltrán, C. E., Ramírez-Cedillo, E., & Ortega-Lara, W. (2021). Reinforcement of alginate-gelatin hydrogels with bioceramics for biomedical applications: A comparative study. *Gels*, *7*(4). https://doi.org/10.3390/gels7040184

Bendtsen, S. T., Quinnell, S. P., & Wei, M. (2017). Development of a novel alginate-polyvinyl alcohol-hydroxyapatite hydrogel for 3d bioprinting bone tissue engineered scaffolds. *Journal of Biomedical Materials Research Part A*, *105*(5), 1457–1468. https://doi.org/10.1002/jbm.a.36036

Bilici, Ç., Altunbek, M., Afghah, F., Tatar, A. G., & Koç, B. (2023). Embedded 3d printing of cryogel-based scaffolds. *ACS Biomaterials Science & Engineering*, *9*(8), 5028–5038. https : / / pubs . acs .org/ doi / full /10.1021/ acsbiomaterials.3c00751

Bojorges, H., López-Rubio, A., Martínez-Abad, A., & Fabra, M. J. (2023). Overview of alginate extraction processes: Impact on alginate molecular structure and techno-functional properties. *Trends in Food Science & Technology*, *140*, 104142. https://doi.org/https://doi.org/10.1016/j.tifs.2023.104142

Chen, Z.-Y., Wu, Y.-Y., Liu, S.-C., Li, Y., Guan, Z.-Q., Cao, C.-F., Zhang, G.-D., Tuten, B. T., Gao, J.-F., Shi, Y.-Q., et al. (2025). Pottery-inspired flexible fire-shielding ceramifiable silicone foams for exceptional long-term thermal protection. *Advanced Functional Materials*, *35*(3), 2413362. https :// doi .org/10.1002/adfm. 202413362

da Silva Fernandes, R., de Moura, M. R., Glenn, G. M., & Aouada, F. A. (2018). Thermal, microstructural, and spectroscopic analysis of ca2+ alginate/clay nanocomposite hydrogel beads. *Journal of Molecular Liquids*, *265*, 327–336. https://doi.org/10.1016/j.molliq.2018.06.005

Davis, T. A., Volesky, B., & Mucci, A. (2003). A review of the biochemistry of heavy metal biosorption by brown algae.

Water Research, *37*(18), 4311–4330. https://doi.org/https://doi.org/10.1016/S0043-1354(03)00293-8 De la Cruz, L. G., Abt, T., León, N., & Sánchez-Soto, M. (2024). Radially and axially oriented ammonium alginate

aerogels modified with clay/tannic acid and crosslinked with glutaraldehyde. *Gels*, *10*(8). https://www. mdpi.com/2310-2861/10/8/526

Del, M. D. L. A. O., Medina, M., Duque, R., Ortega, A. A. J., Castillero, L., et al. (2024). Advancing sustainable construction: Insights into clay-based additive manufacturing for architecture, engineering, and construction. In *Developments in clay science and construction techniques*. IntechOpen. https://www.intechopen.com/ chapters/1186343

Dove, C. A., Bradley, F. F., & Patwardhan, S. V. (2016). Seaweed biopolymers as additives for unfired clay bricks. *Materials and Structures*, *49*, 4463–4482. https://doi.org/10.1617/s11527-016-0801-0

Eger, A. M., Marzinelli, E. M., Beas-Luna, R., Blain, C. O., Blamey, L. K., Byrnes, J. E., Carnell, P. E., Choi, C. G., HessingLewis, M., Kim, K. Y., et al. (2023).

The value of ecosystem services in global marine kelp forests. *Nature communications*, *14*(1), 1894. https://doi.org/10.1038/s41467-023-37385-0

Fan, Q., Ou, R., Hao, X., Deng, Q., Liu, Z., Sun, L., Zhang, C., Guo, C., Bai, X., & Wang, Q. (2022). Water-induced self-assembly and in situ mineralization within plant phenolic glycol-gel toward ultrastrong and multifunctional thermal insulating aerogels [PMID: 35653439]. *ACS Nano*, *16*(6), 9062–9076. https://doi.org/ 10.1021/acsnano.2c00755

Fischer, F. G., & Dörfel, H. (1955). *Biological Chemistry*, *302*(Jahresband), 186–203. https://doi.org/doi:10.1515/ bchm2.1955.302.1-2.186

Franklin, M. J., Nivens, D. E., Weadge, J. T., & Howell, P. L. (2011). Biosynthesis of the pseudomonas aeruginosa extracellular polysaccharides, alginate, pel, and psl. *Frontiers in microbiology*, *2*, 167. https://doi.org/10. 3389/ fmicb.2011.00167

Gady, O., Poirson, M., Vincent, T., Sonnier, R., & Guibal, E. (2016). Elaboration of light composite materials based on alginate and algal biomass for flame retardancy: Preliminary tests. *Journal of Materials Science*, *51*, 10035–10047. https://doi.org/10.1007/s10853-016-0230-z

Galán-Marín, C., Rivera-Gómez, C., & Petric, J. (2010a). Clay-based composite stabilized with natural polymer and fibre. *Construction and Building Materials*, *24*(8), 1462–1468. https://doi.org/https://doi.org/10.1016/j. conbuildmat.2010.01.008

Galán-Marín, C., Rivera-Gómez, C., & Petric, J. (2010b). Clay-based composite stabilized with natural polymer and fibre. *Construction and Building Materials*, *24*(8), 1462–1468. https://doi.org/https://doi.org/10.1016/j. conbuildmat.2010.01.008

Houben, H., & Guillaud, H. (1992). *Earth construction: A comprehensive guide*. Intermediate Technology Publications. https://archive.org/ details/5226-earth-construction-technology/page/21/mode/2up

Huarachi, D. A. R., Gonçalves, G., de Francisco, A. C., Canteri, M. H. G., & Piekarski, C. M. (2020). Life cycle assessment of traditional and alternative bricks: A review. *Environmental Impact Assessment Review*, *80*, 106335. https://doi.org/https://doi.org/10.1016/j.eiar.2019.106335

Hurtado, A., Aljabali, A. A., Mishra, V., Tambuwala, M. M., & Serrano-Aroca, Á. (2022). Alginate: Enhancement strategies for advanced applications. *International Journal of Molecular Sciences*, *23*(9), 4486. https:// doi.org/10.3390/ijms23094486

Jelle, B. P. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions– properties, requirements and possibilities. *Energy and buildings*, *43*(10), 2549–2563. https://doi.org/10. 1016/j.enbuild.2011.05.015

Jin, H., Zhou, X., Xu, T., Dai, C., Gu, Y., Yun, S., Hu, T., Guan, G., & Chen, J. (2020). Ultralight and hydrophobic palygorskite-based aerogels with prominent thermal insulation and flame retardancy. *ACS Applied Materials & Interfaces*, *12*(10), 11815–11824. https://doi.org/10.1021/acsami.9b20923

Karaduman, F. R., Türk Çulha, S., & Horzum, N. (2022). Algal nanofibers: Current status and recent developments. *Materials Today Communications*, *33*, 104248. https://doi.org/https://doi.org/10.1016/j.mtcomm. 2022.104248

Koebel, M., Rigacci, A., & Achard, P. (2012). Aerogel-based thermal superinsulation: An overview. *Journal of sol-gel science and technology*, *63*, 315–339. https://doi.org/10.1007/s10971-012-2792-9

Kumari, N., & Mohan, C. (2021). Basics of clay minerals and their characteristic properties. *Clay Clay Miner*, *24*(1), 1–29. https://www.intechopen.com/chapters/76780

Kyaw Oo D'Amore, G., Caniato, M., Travan, A., Turco, G., Marsich, L., Ferluga, A., & Schmid, C. (2017). Innovative thermal and acoustic insulation foam from recycled waste glass powder. *Journal of Cleaner Production*, *165*, 1306–1315. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.07.214

Lacoste, C., El Hage, R., Bergeret, A., Corn, S., & Lacroix, P. (2018). Sodium alginate adhesives as binders in wood fibers/textile waste fibers biocomposites for building insulation. *Carbohydrate Polymers*, *184*, 1–8. https: //doi.org/https://doi.org/10.1016/j.carbpol.2017.12.019

Lagzdiņš, A., Zilaucs, A., Beverte, I., & Andersons, J. (2022). Modeling the nonlinear deformation of highly porous cellular plastics filled with clay nanoplatelets. *Materials*, *15*(3), 1033. https://doi.org/10.3390/ma15031033 Lee, K. Y., & Mooney, D. J. (2012). Alginate: Properties and biomedical applications. *Progress in Polymer Science*, *37*(1), 106–126. https://doi.org/https://doi.org/10.1016/j.progpolymsci.2011.06.003

Leu Alexa, R., Ianchis, R., Savu, D., Temelie, M., Trica, B., Serafim, A., Vlasceanu, G. M., Alexandrescu, E., Preda, S., & Iovu, H. (2021). 3d printing of alginate-natural clay hydrogel-based nanocomposites. *Gels*, *7*(4), 211. https://doi.org/10.3390/gels7040211

Liu, Q., Li, Q., Xu, S., Zheng, Q., & Cao, X. (2018). Preparation and properties of 3d printed alginate–chitosan polyion complex hydrogels for tissue engineering. *Polymers*, *10*(6), 664. https://doi.org/10.3390/polym10060664

Liu, S., Bastola, A. K., & Li, L. (2017). A 3d printable and mechanically robust hydrogel based on alginate and graphene oxide. *ACS applied materials & interfaces*, *9*(47), 41473–41481. https : // pubs . acs .org/ doi / full/10.1021/acsami.7b13534

Mao, S., Kan, A., & Wang, N. (2020). Numerical analysis and experimental investigation on thermal bridge effect of vacuum insulation panel. *Applied Thermal Engineering*, *169*, 114980. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2020.114980

Marsh, A. T., & Kulshreshtha, Y. (2022). The state of earthen housing worldwide: How development affects attitudes and adoption. *Building Research & Information*, *50*(5), 485–501. https://doi.org/10.1080/09613218.2021.1953369

Mateus, R., Fernandes, J., & Teixeira, E. R. (2020). Environmental life cycle analysis of earthen building materials (S. Hashmi & I. A. Choudhury, Eds.), 63–68. https://doi.org/10.1016/B978-0-12-803581-8.11459-6

Michel, G., Tonon, T., Scornet, D., Cock, J. M., & Kloareg, B. (2010). The cell wall polysaccharide metabolism of the brown alga ectocarpus siliculosus. insights into the evolution of extracellular matrix polysaccharides in eukaryotes. *New Phytologist*, *188*(1), 82–97. https://doi.org/10.1111/j.1469-8137.2010.03374.x

Minas, C., Carpenter, J., Freitag, J., Landrou, G., Tervoort, E., Habert, G., & Studart, A. R. (2019). Foaming of recyclable clays into energy-efficient low-cost thermal insulators. *ACS Sustainable Chemistry & Engineering*, *7*(18), 15597–15606. https://doi.org/10.1021/acssuschemeng.9b03617

Minke, G. (2006). *The properties of earth as a building material*. Birkhäuser. https://doi.org/doi:10.1007/3-76437873-5_2

Nazrun, T., Hassan, M. K., Hossain, M. D., Ahmed, B., Hasnat, M. R., & Saha, S. (2024). Application of biopolymers as sustainable cladding materials: A review. *Sustainability*, *16*(1), 27. https://doi.org/10.3390/su16010027

Ni, J., Li, S.-S., & Geng, X.-Y. (2022). Mechanical and biodeterioration behaviours of a clayey soil strengthened with combined carrageenan and casein. *Acta Geotechnica*, *17*(12), 5411–5427. https : // doi .org/10.1007/s11440-022-01588-4

Palen, B., Kolibaba, T. J., Brehm, J. T., Shen, R., Quan, Y., Wang, Q., & Grunlan, J. C. (2021). Clay-filled polyelectrolyte complex nanocoating for flame-retardant polyurethane foam [PMID: 33817460]. *ACS Omega*, *6*(12), 8016–8020. https://doi.org/10.1021/acsomega.0c05354

Palumbo, M., Lacasta, A., Giraldo, M., Haurie, L., & Correal, E. (2018). Bio-based insulation materials and their hygrothermal performance in a building envelope system (etics). *Energy and Buildings*, *174*, 147–155. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.06.042

Palumbo, M., Lacasta, A., Navarro, A., Giraldo, M., & Lesar, B. (2017). Improvement of fire reaction and mould growth resistance of a new bio-based thermal insulation material. *Construction and Building Materials*, *139*, 531–539. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.11.020

Rabbat, C., Awad, S., Villot, A., Rollet, D., & Andrès, Y. (2022). Sustainability of biomass-based insulation materials in buildings: Current status in france, end-of-life projections and energy recovery potentials. *Renewable and Sustainable Energy Reviews*, *156*, 111962. https://doi.org/10.1016/j.rser.2021.111962

Rabillé, H., Torode, T. A., Tesson, B., Le Bail, A., Billoud, B., Rolland, E., Le Panse, S., Jam, M., & Charrier, B. (2019). Alginates along the filament of the brown alga ectocarpus help cells cope with stress. *Scientific reports*, *9*(1), 12956. https://doi.org/10.1038/s41598-019-49427-z

Raja, P., Murugan, V., Ravichandran, S., Behera, L., Mensah, R. A., Mani, S., Kasi, A., Balasubramanian, K. B. N., Sas, G., Vahabi, H., et al. (2023). A review of sustainable bio-based insulation materials for energy-efficient buildings. *Macromolecular Materials and Engineering*, *308*(10), 2300086. https : / / doi . org / 10 . 1002 / mame.202300086

Schiavoni, S., D′Alessandro, F., Bianchi, F., & Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. *Renewable and Sustainable Energy Reviews*, *62*, 988–1011. https://doi.org/10.1016/j.rser.2016.05.045

Shubbar, A. A., Sadique, M., Kot, P., & Atherton, W. (2019). Future of clay-based construction materials – a review. *Construction and Building Materials*, *210*, 172–187. https : / / doi . org / https : / / doi . org / 10 . 1016 / j . conbuildmat.2019.03.206

Singh, J., & Saxena, R. C. (2015). An introduction to microalgae: Diversity and significance. In *Handbook of marine microalgae* (pp. 11–24). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-800776-1.00002-9

Suganya, T., Varman, M., Masjuki, H., & Renganathan, S. (2016). Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. *Renewable and Sustainable Energy Reviews*, *55*, 909–941. https://doi.org/10.1016/j.rser.2015.11.026

Synytsya, A., Čopíková, J., Kim, W. J., & Park, Y. I. (2015). Cell wall polysaccharides of marine algae. *Springer handbook of marine biotechnology*, 543–590. doi.org/10.1007/978-3-642-53971-8_22

TG, Y. G., Ballupete Nagaraju, S., Puttegowda, M., Verma, A., Rangappa, S. M., & Siengchin, S. (2023). Biopolymerbased composites: An eco-friendly alternative from agricultural waste biomass. *Journal of Composites Science*, *7*(6), 242. https://doi.org/10.3390/jcs7060242

(UNEP), U. N. E. P. (2022). *2022 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector* (tech. rep. No. ISBN 978-92-807-3984-8). United Nations Environment Programme / Global Alliance for Buildings and Construction. Nairobi. %5Curl%7Bhttps://globalabc.org/sites/default/files/2022-11/FULL%20REPORT_2022%20Buildings-GSR_1.pdf%7D

United Nations Environment Programme, I. R. P. (2024-02). Global resources outlook 2024 bend the trend: Pathways to a liveable planet as resource use spikes. https://wedocs.unep.org/20.500.11822/44901

Veeraprabahar, J., Mohankumar, G., Kumar, S. S., & Sakthivel, S. (2022). Development of natural coir/jute fibers hybrid composite materials for automotive thermal insulation applications. *Journal of Engineered Fibers and Fabrics*, *17*, 15589250221136379. https://doi.org/10.1177/15589250221136379

Vijayan, S., Wilson, P., Prabhakaran, K., Salih, A. A., & Joseph, K. (2020). Preparation of ceramic foam spheres by injection molding of emulsions. *Journal of Asian Ceramic Societies*, *8*(1), 21–28. https://doi.org/10.1080/21870764.2019.1695558

Villasmil, W., Fischer, L. J., & Worlitschek, J. (2019). A review and evaluation of thermal insulation materials and methods for thermal energy storage systems. *Renewable and Sustainable Energy Reviews*, *103*, 71–84. https://doi.org/https://doi.org/10.1016/j.rser.2018.12.040

Volschenk, G., O'Shea, M., & Shaughnessy, B. (2024). A novel approach to thermal insulation modelling in soft and medium vacuum insulation systems. *Cryogenics*, *144*, 103946. https://doi.org/10.1016/j.cryogenics. 2024.103946

Wang, D., Peng, H., Yu, B., Zhou, K., Pan, H., Zhang, L., Li, M., Liu, M., Tian, A., & Fu, S. (2020). Biomimetic structural cellulose nanofiber aerogels with exceptional mechanical, flame-retardant and thermal-insulating properties. *Chemical Engineering Journal*, *389*, 124449. https://doi.org/https:// doi.org/10.1016/j.cej. 2020.124449

Wawszczak, A., Kocki, J., & Kołodyńska, D. (2024). Alginate as a sustainable and biodegradable material for medical and environmental applications—the case studies. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, *112*(9), e35475. https://doi.org/10.1002/jbm.b.35475

Wolf, A., Rosendahl, P. L., & Knaack, U. (2022). Additive manufacturing of clay and ceramic building components. *Automation in Construction*, *133*, 103956. https://doi.org/10.1016/j.autcon.2021.103956

Wu, Z., Su, X., Xu, Y., Kong, B., Sun, W., & Mi, S. (2016). Bioprinting three-dimensional cell-laden tissue constructs with controllable degradation. *Scientific reports*, *6*(1), 24474. https://doi.org/10.1038/srep24474

Zdiri, K., Cayla, A., Elamri, A., Erard, A., & Salaun, F. (2022). Alginate-based bio-composites and their potential applications. *Journal of Functional Biomaterials*, *13*(3), 117. https://doi.org/10.3390/jfb13030117

Zhu, J., Li, X., Li, D., & Jiang, C. (2022). Thermal insulation and flame retardancy of the hydroxyapatite nanorods/sodium alginate composite aerogel with a double-crosslinked structure [PMID: 36166410]. *ACS Applied Materials & Interfaces*, *14*(40), 45822–45831. https://doi.org/10.1021/acsami.2c12254

Zia, F., Salman, M., Ali, M., Iqbal, R., Rasul, A., Najam-ul-Haq, M., Asgher, M., & Zia, K. M. (2020). Chapter 8 alginate-based bionanocomposites. In K. Mahmood Zia, F. Jabeen, M. N. Anjum, & S. Ikram (Eds.), *Bionanocomposites* (pp. 173–205). Elsevier. https://doi.org/https://doi.org/10.1016/ B978-0-12-8167519.00008-8

WHY ARCHITECTS (DON'T) SKETCH WITH CLIENTS: A SURVEY OF DIGITAL FREEHAND PRACTICES

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ABSTRACT:

This study examines architect–client (A–C) communication through digital architectural sketching. Digital sketching represents an evolving mode of architectural expression. It builds on the cognitive and metaphorical foundations of traditional freehand sketching, while expanding opportunities for shared understanding and co-ideation. It shifts the medium from paper to screen or spatial interface, and repositions the sketch as a tool for active, real-time engagement.

The research is based on a structured quantitative survey (n=70+). It included 14 scaled items about digital sketching in client communication. It also included three open-ended questions. These captured how architects understand digital sketching and what limitations they perceive. All participants were freelance architects in active practice. Their graduation years ranged from 1993 to 2023.

Previous research has primarily focused on communication technologies such as VR and BIM, often outside the context of direct architect–client interaction. Studies on sketching technologies rarely address this interpersonal setting. In contrast, digital sketching in early-stage communication builds on the values of freehand drawing—such as speed and ambiguity—while supporting interaction and mutual understanding between both parties. It also integrates new possibilities, including the use of photographs or 3D data as a base.

The survey showed that approximately 30% of respondents actively sketch with clients using digital tools. Female architects rated the importance of sketching in client communication approximately two points higher, on average, than their male counterparts. Hardware cost was not identified as a significant barrier. More commonly cited challenges included time constraints, a steep learning curve, and the mental effort of sketching while communicating and co-ideating.

This mapping of real practitioner perceptions helps uncover why digital sketching is still rarely used in A–C early design conversations. It brings a grounded understanding of the barriers and expectations architects experience when using digital sketching tools in interactions with clients. This study also lays foundational insights for tool development and better understanding of the communication role of sketching in real A–C practice.

Keywords: Digital Architectural Sketching, Architect-Client Communication, Co-ideation, Design Clarity, Adoption Barriers, Quantitative Survey

1. INTRODUCTION

Effective communication between architect and client is the cornerstone of successful design and the entire project (Taleb et al., 2017). Sketching plays a crucial role in this dialogue, not only as a tool for the designer's thinking (Lawson, 1980), but above all as a key means of communication (Gabriel & Maher, 2002). While traditional sketching on paper has its irreplaceable place, in the digital age it faces limitations in terms of flexibility, sharing, and interactivity. With the advent of digital tools, new possibilities are opening up for digital architectural sketching (DAS), which promises to overcome these barriers and involve the client more effectively in the process.

Digital sketching is overshadowed by other forms of visualization and the tools themselves. Current practice often focuses on final outputs such as photorealistic renders (e.g., in Twinmotion, Lumion) or content generated by artificial intelligence. However, these methods are primarily presentation-oriented and replace traditional visualization rather than the sketching process itself. Perhaps even greater competition comes from technocratic thinking and the pursuit of ever-new tools for 2D sketching (e.g., Morpholio, Concepts, Procreate) or 3D sketching (Feather, Mental Canvas). In this constant search for the "perfect" tool, the primary essence of sketching is forgotten—communication dialogue and the search for solutions through visual means. The very act of digital freehand sketching, as an interactive and lively process, paradoxically remains in the shadow of the tools that are supposed to serve it.

The relevance of this topic is underscored by the fundamental understanding of sketching as a universal language. In literature, sketching is described as a means of negotiation and joint design creation (McDonnell, 2009). It is a "conversation with the situation," where each line elicits a response and advances the thought process (Schön, 1983;

Goldschmidt, 2003). DAS has the potential to expand this dialogue and convey it to the client, who can thus become an active participant rather than a passive recipient. The study of DAS is therefore a study of the evolution of this fundamental architectural language.

The aim of this article is to map how architects in contemporary practice actually perceive and use digital architectural sketching. This research follows on from a previous qualitative study (Dzurilla & Achten, 2022), in which basic problem areas were identified through interviews. Through the quantitative questionnaire survey presented here, we now seek to verify these areas, identify key factors influencing architects' decisions, and uncover the main barriers—whether technological, procedural, or mental. We are interested in the reasons why DAS is still so little used in direct communication with clients, even though its potential for improving design clarity and strengthening collaboration is obvious.

2. RELATED WORK / LITERATURE REVIEW

Summary of studies on traditional sketching and its role in the design process. Traditional sketching is thoroughly described in the literature as a cognitive tool that externalizes ideas and promotes "reflection in action" (Schön, 1983). Its power lies in its speed and "fruitful ambiguity" (Goldschmidt, 2003), which leaves room for interpretation and promotes lateral thinking (Goel, 1995). A sketch is perceived as a physical artifact whose haptic properties strengthen the connection between the hand, eye, and mind (Chrzanowska, 2019). In communication, it serves as a bridge between the expert and the layperson, but at the same time suffers from limitations in modifiability and scale accuracy (Bilda & Demirkan, 2003).

Digital tools: what is known and what is missing in digital freehand sketching. Digital sketching (DAS) takes over the spontaneity of traditional drawing, but enriches it with new possibilities such as layers, easy editing, and instant sharing (Verdú et al., 2013). In theory, DAS extends traditional sketching with a "processor" (Dzurilla & Achten, 2021). However, research often focuses on technical aspects, overlooking communication dynamics. It is unclear whether advantages such as easy editing actually lead to better understanding or, conversely, may lead to premature closure of the design (Cardoso et al., 2009). Furthermore, the use of complex tools can increase cognitive load (Sweller, 1988), making it difficult to listen to the client at the same time.

Research gaps:

- Lack of data on the actual use of DAS in client communication. Although there are studies comparing digital and traditional sketching from a cognitive perspective, systematic research focused on the actual use of DAS in everyday practice when communicating with clients is very limited.
- Lack of architects' perspectives on why they sketch/do not sketch with clients. Most studies focus on the performance of tools, not on the subjective perceptions and attitudes of the architects themselves. There is a lack of qualitative data that would reveal their motivations and concerns. This "habitus shock" (Siva & London, 2012) – i.e., communication friction between the expert and the layperson – and the fear of it may be a key barrier.
- The gender perspective is not addressed in prior research. The question of whether there are differences in the perception and use of communication tools between male and female architects has not yet been systematically investigated in the context of DAS.

Anchoring research in the transition from representation to interaction (co-ideation). This research understands DAS not only as a tool for creating representations, but as a medium for interaction. It shifts from viewing a sketch as a final product to viewing sketching as a collaborative process (co-ideation) where both parties actively shape the design. Thanks to its flexibility and interactivity, DAS has the potential to support this transition and transform a one-way presentation into a two-way dialogue. The aim is therefore to explore the extent to which architects perceive and utilize this interactive potential.

3. METHODOLOGY

3.1. Research design

This article presents findings from a quantitative questionnaire survey that focused on architects' attitudes and experiences with digital sketching (DAS). The design of the questionnaire itself was informed by findings from previous qualitative research (Dzurilla & Achten, 2022), specifically from semi-structured interviews with 23 architects, which ensured the relevance and depth of the topics explored. The aim of the questionnaire was to empirically verify and quantify the trends that emerged from the interviews on a broad sample of 70 respondents. The structure of the questionnaire included demographic data, open-ended questions to capture individual definitions and barriers, and 14 specific statements rated on a Likert scale that focused on key aspects of DAS use in practice.

3.2. Data collection

Data collection was conducted via an online questionnaire compiled on the Google Forms platform, with questions based on topics identified in previous interviews. The questionnaire consisted of a demographic section, three open-ended questions, and 14 statements rated on a Likert scale (1-10). The questionnaire was pilot tested prior to deployment, which led to several adjustments to ensure clarity.

It was necessary to consistently distinguish between the terms "digital sketching" (process) and "digital sketch" (output). Some ambiguous statements were simplified, and key phenomena, such as the relationship between comfort and sketching skill or between clarity for the client and the approval process, were deliberately verified by several differently worded statements. These statements were strategically placed in the questionnaire to prevent respondents from immediately connecting them and to better track the consistency or inconsistency of their opinions.

3.3. Sample of respondents

The target group was practicing architects with at least one year of experience, ideally freelancers, with no geographical restrictions. The questionnaire was distributed online via the Visuin Studio (the first author's studio focused on educating architects) mailing list and professional groups on LinkedIn and Facebook in order to reach the widest and most diverse group of architects possible. Data collection took place from January 14, 2022, to April 30, 2025, with the longer collection period motivated by the desire to obtain a sufficient number of responses. A total of 70 completed questionnaires were used for the analysis. In terms of gender composition, men (41 respondents) outnumbered women (29 respondents).

3.4. Data analysis

Descriptive statistics were used for quantitative data from the Likert scale; for each statement, the number of responses for each scale value (1-10) was counted. This data was then visualized using bar charts to identify general trends in respondents' attitudes. Responses to open-ended questions were subjected to basic content (thematic) analysis. This process involved reading all responses to a given question, identifying recurring themes and keywords, and then categorizing them. Google Sheets and Apple Numbers were used for graphical processing and basic data analysis.

4. RESULTS

4.1. Overall rate of DAS use with clients

One of the most notable findings from the questionnaire survey is the relatively low rate of adoption of digital sketching in direct communication with clients. Approximately 60% of respondents said that they do not actively use digital sketching with clients or do not even recommend this practice. Only about 30% of the architects surveyed are active users, while the remaining 10% can imagine using this technique in the future (Figure 1).

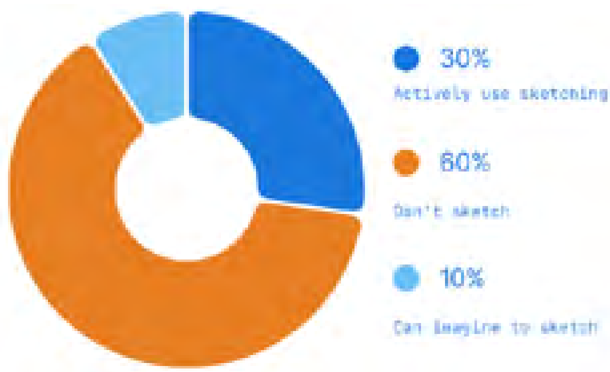

Figure 1: A pie chart illustrating the 60/30/10 ratio.

This result contrasts interestingly with another finding, whereby the majority of architects (with a median rating of 8 out of 10) also agree with the statement that sketching with clients is an important part of architectural practice (Figure 2). This discrepancy between recognition of theoretical importance and low practical implementation suggests the existence of significant barriers that prevent wider use of DAS as a communication tool.

Figure 2: Results to statement: "Sketching with a client is an important part of an architect's practice (any form)."

4.2. The paradox of comfort and comprehensibility

A noteworthy finding is the internal conflict in architects' attitudes between the perceived benefit to the client and their own user comfort. On the one hand, respondents strongly agree with the statement that *"digital sketching helps with clarity when communicating with the client."* On the other hand, however, the data show that it is more important for them *"how they sketch on a given device than whether it is representative for the client"* (Figure 3).

This paradox is further illuminated by open-ended responses in which architects mention high mental load: *"Digital sketching requires intense concentration when you are trying to listen to and respond to the client."* It therefore seems that the main obstacle is not a lack of confidence in the effectiveness of DAS for the client, but rather a fear of cognitive overload and a preference for their own smooth work process over potentially chaotic, albeit perhaps more understandable for the client, live interaction.

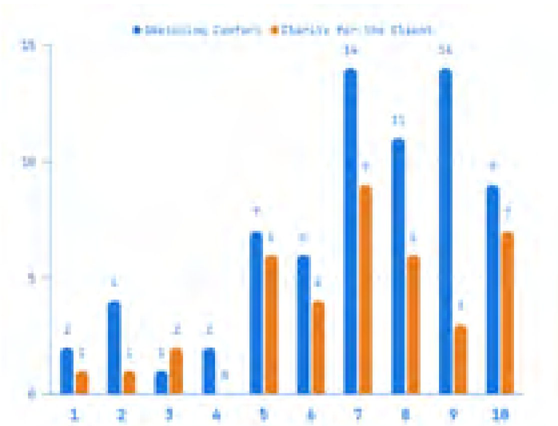

Figure 3:Sketching comfort vs. clarity for the client. (Blue values) „It is more important how I sketch on a given device than whether it is representative for the client" vs. „Digital sketching can increase clarity in front of the client" (Orange values).

4.3. Implementation barriers vs. price

Analysis of the responses shows that the main obstacles to wider adoption of DAS are not primarily financial, but rather procedural and mental (Figure 4). Although the median rating for statements relating to price and the learning curve is 7, the distribution of responses reveals a significant difference. In the case of the statement *"Price determines whether*

I will purchase a digital sketching tool," respondents' opinions are more spread out, with a significant representation even in the lower values of the scale, suggesting that price is not a decisive factor for a significant portion of architects. On the other hand, for the statement *"The learning curve determines whether I use a digital sketching tool,"* the answers are more concentrated in the higher values (7, 8, 10).

This shows that the difficulty of implementation is perceived as a more consistent and significant barrier. The open-ended responses indicate that the biggest problem is the time and mental effort required to learn a new tool and integrate it into established workflows. One respondent summed it up by saying, *"The biggest challenge for me is finding the time and mental space to learn a new system amid the daily pressure of projects."* It therefore appears that the investment of time and energy in implementation is perceived as a greater obstacle than the financial investment itself.

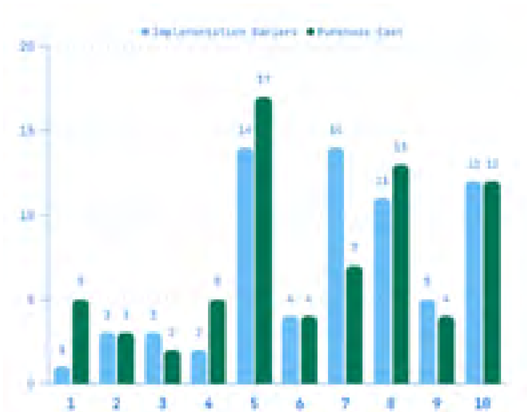

Figure 4: Barriers: Implementation barrier vs. purchase cost. (Green values) "Price determines whether I will purchase a digital sketching tool," vs. (Light values) "The learning curve determines whether I use a digital sketching tool."

4.4. Availability and portability as a condition of use

The practical aspects of the tool play a crucial role in its actual use. Data from the questionnaire show that the weight and portability of the device are important to most architects, with a median rating of 9 out of 10 (Figure 5). The ability to have the tool with you at all times, whether on a construction site or in a meeting, is seen as.

Responses to the question of whether it is important to have the device with you at all times were strongly polarized: a large group of respondents (32) consider it absolutely essential (rating 10), while another significant group do not consider it important. This U-curve suggests two different working styles – either architects rely on the constant availability of digital tools, or they perceive them as specialized equipment for specific tasks in the office. For the first group, factors such as weight, size, and durability of the device are therefore decisive.

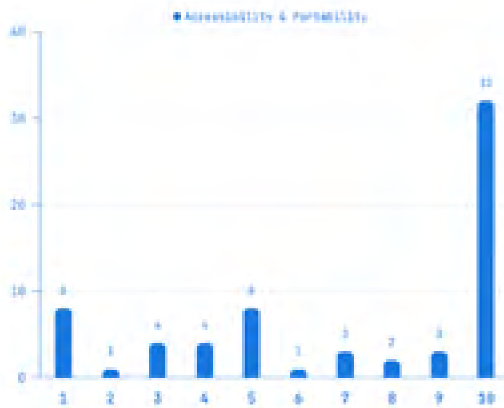

Figure 5: Number of responses for the statement: "The learning curve determines whether I use a digital sketching tool."

4.5. Influence of drawing skills and other barriers

The questionnaire results strongly suggest that digital tools are not perceived as a substitute for basic drawing skills (Figure 6). The vast majority of respondents (with a median rating of 8) agree with the statement that *"drawing skill can significantly influence the use of digital sketching."*

The open-ended responses reveal other, more subtle barriers. These include concerns about client reaction *("the client may take the digital sketch too literally")*, a different sensory experience compared to traditional media (*"I miss the contact with paper"),* or practical concerns about dependence on technology and the risk of data loss. Together, these factors contribute to mental stress and uncertainty that can discourage architects from sketching live in front of clients.

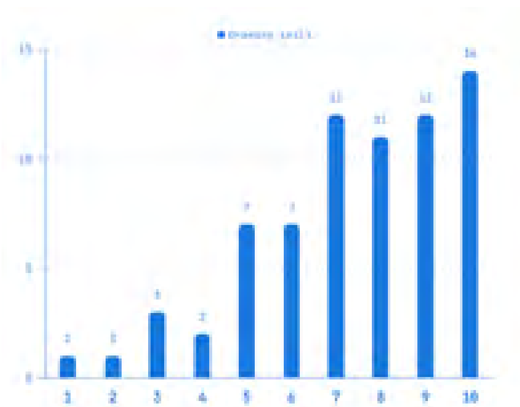

Figure 6: Number of responses for the statement: *"drawing skill can significantly influence the use of digital sketching."*

5. DISCUSSION

5.1. Interpretation of results

The questionnaire results reveal a fundamental discrepancy between the theoretical recognition of the potential of digital sketching and its low practical implementation in communication with clients. Although architects perceive sketching as an important part of their practice and believe that DAS can increase clarity for the client, only a minority (30%) actively use it. Key findings suggest that the main causes of this situation are not economic or technological in the narrow sense, but rather psychological and procedural.

The decisive obstacle seems to be the prioritization of personal comfort over concerns about the high mental load associated with simultaneous drawing and listening. Added to this is the difficulty of implementing new tools into established procedures. Architects seem to be caught in a paradox: they know what could help the client, but they hesitate to undergo the associated discomfort and risk of disrupting the flow of their work.

5.2. Gender differences in context

An interesting side finding of the survey is the suggested difference in attitudes between male and female architects. Although the data does not allow for in-depth statistical analysis, the responses suggest that women tend to attach greater importance to sketching in communication with clients (Figure 7).

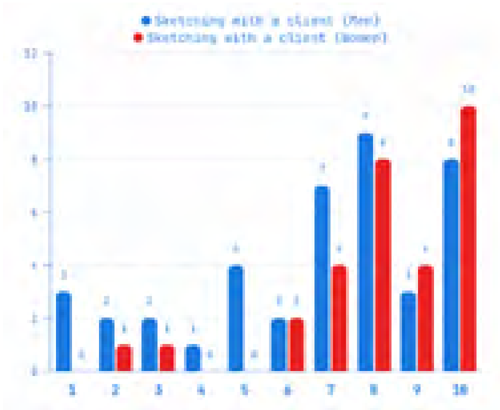

Figure 7: Statements about sketching with clients, comparing the genders.

This observation could be related to theories that suggest different communication styles and a greater emphasis on relationship building and empathy in women's professional approach. Sketching could thus be perceived not only as a technical tool, but also as a relational tool that helps reduce information asymmetry and build trust between the expert and the layperson. However, this aspect deserves further, targeted research.

5.3. Connection to existing theory

The barriers identified strongly resonate with existing theoretical concepts. The fear of mental overload corresponds to the theory of cognitive load, which states that an overly complex task (sketching + listening + tool control) reduces performance. Resistance to abandoning established practices and fear of client reaction may be a manifestation of an effort to avoid "habitus shock" (Siva & London, 2012), i.e., communication friction between the worlds of the expert and the layperson. On the other hand, the potential of DAS to promote dialogue and reduce client uncertainty is consistent with works that emphasize the value of speed and the "fruitful ambiguity" of sketching for joint solution-seeking (Goldschmidt, 2003). Our results thus empirically confirm that while the theoretical potential of DAS for improving communication is considerable, practical obstacles lie deep in the psychology and working habits of architects.

6. CONCLUSION AND FUTURE RESEARCH

6.1. Summary of main findings

This survey showed that despite technological possibilities and recognition of the importance of sketching, active use of digital sketching for communication with clients remains low. The main barriers are not financial, but rather practical and psychological, related to the difficulty of implementation, mental strain, and concerns about disrupting one's own comfort. An interesting gender dimension in the perception of the role of sketching also emerged. The potential of DAS to improve communication is therefore high, but its fulfillment is hampered by deeply ingrained work habits and psychological barriers.

6.2. Recommendations

Based on the findings, recommendations can be formulated for two main groups. For software and hardware developers, it is crucial to focus on tools with a low learning curve and minimal cognitive load. The physical form of the device is also essential—its portability, low weight, and durability are prerequisites for effective use, for example, directly on site with the client, and support smooth and uninterrupted interaction.

For architectural practice, it is recommended to pay attention not only to technological aspects, but above all to the development of communication skills and the willingness to integrate DAS into the early stages of design as a tool for building trust and understanding with the client, even at the cost of temporarily leaving one's comfort zone.

6.3. Suggestions for future research

This study opens up several avenues for future research that could build on its findings and limitations. It is desirable to extend the research to a larger and more geographically diverse sample of architects in order to verify the validity of the results in different cultural and professional contexts. Furthermore, there is an opportunity for a more in-depth demographic analysis that would focus specifically on the influence of length of practice and gender on the perception and adoption of DAS. Such research could examine in more detail how attitudes toward digital tools change at different stages of professional careers and between men and women.

6.4. Conclusion

The successful integration of digital sketching into practice ultimately does not lie in finding the perfect tool, but in changing mindsets. The key is understanding that DAS is not just a technology for more efficient production, but above all a technique for deeper and more comprehensible dialogue. Overcoming the identified barriers therefore requires not only better software, but also a willingness on the part of architects to perceive sketching as a service to the client that prioritizes mutual understanding over personal comfort or aesthetic perfection.

7. REFERENCES

Bilda, Z., & Demirkan, H. (2003). An Insight on Designers' Sketching Activities in Traditional versus Digital Media. *Design Studies, 24*(1), 27-50.

Cardoso, C., Badke-Schaub, P., & Luz, A. (2009). Design fixation on non-verbal stimuli: The influence of simple vs rich pictorial information on design problem-solving. *Proceedings of the ASME Design Engineering Technical Conference, 8*(PARTS A AND B), 995–1002.

Chrzanowska, O. (2019). The role of sketching within the process of creative maturation of an architect in 21st century sketching from nature in cognitive development. *Interdyscyplinarne Konteksty Pedagogiki Specjalnej, (26)*, 395-420.

Dzurilla, D., & Achten, H. (2021). What is Architectural Digital Sketch? A systematic inventory. In *Proceedings of the 39th eCAADe Conference* (Vol. 1, pp. 403-414).

Dzurilla, D., & Achten, H. (2022). What"s Happening to Architectural Sketching? Interviewing architects about transformation from traditional to digital architectural sketching as a communication tool with clients. In B. Pak, G. Wurzer, & R. Stouffs (Eds.), *Co-creating the Future: Inclusion in and through Design - Proceedings of the 40th Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2022)* (Vol. 1, pp. 389–398). eCAADe. https://doi.org/10.52842/conf.ecaade.2022.1.389

Gabriel, G. C., & Maher, M. L. (2002). Coding and modelling communication in architectural collaborative design. *Automation in Construction, 11*(2), 199–211.

Goel, V. (1995). *Sketches of thought.* MIT Press.

Goldschmidt, G. (2003). The backtalk of self-generated sketches. *Design Issues, 19*(1), 72–88.

Lawson, B. (1980). *How designers think.* Architectural Press.

Llopis, N. C., Vivas, J. M. R., & Ferrándiz, J. M. S. (2013). Digital versus traditional sketching: A neurological perspective. *Design Studies, 34*(5), 629-646.

McDonnell, J. (2009). Collaborative negotiation in design: A study of design conversations between architect and building users. *CoDesign, 5*(1), 35–50.

Norouzi, N., Shabak, M., Embi, M. R. B., & Khan, T. H. (2014). Participation Problems and Communication Difficulties in Architectural Design Practice. *Applied Mechanics and Materials, 567*, 689–692.

Schön, D. A. (1983). *The Reflective Practitioner: How Professionals Think in Action*. Basic Books.

Siva, J., & London, K. (2012). Client learning for successful architect-client relationships. *Engineering, Construction and Architectural Management, 19*(3), 265–281.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive science, 12*(2), 257-285.

Taleb, H., Ismail, S., Wahab, M. H., & Rani, W. N. M. W. M. (2017). Communication management between architects and clients. *AIP Conference Proceedings, 1891*(1), 020087.

Verdú, E., Ribera, M., & da Rocha e Costa, A. C. (2013). The role of digital sketching in architectural workflows. *International Journal of Architectural Computing, 11*(3), 269-286.

ENHANCING SAND-PLASTIC CONSTRUCTION DESIGN: A RHINO-TO-REVIT INTEROPERABILITY APPROACH USING DYNAMO

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ABSTRACT:

Plastic pollution has become a significant environmental concern over the past decade. Much research has been conducted to address the issue of plastic waste. In the construction sector, the use of plastic as a construction material appears promising, and sand-plastic composites have demonstrated great potential in construction applications. However, these solutions have shown some limitations in the design process, primarily highlighted by challenges in data exchange. In this paper, we present a process that architects can use to analyse their designs incorporating sand-plastic elements and adjust them based on numerical simulation results. Additionally, we address the interoperability challenges between Rhino and Revit by proposing a Dynamo script capable of generating a Revit model with native Revit family components based on a Rhino model. The methodology involves analysing the design and transferring

data from Rhino to Revit using the developed Dynamo script. The resulting Revit model demonstrates significant potential, and the proposed process can be applied to various types of construction systems. However, the current script is unable to generate elements with complex shapes, and future research will focus on overcoming this limitation.

Keywords: Sustainable Construction, Numerical Simulation, Building Information Modelling, Sand-Plastic Composites.

1. INTRODUCTION

Over the last decade, plastic pollution has emerged as a growing environmental concern (Lavkush et al. 2024). In response, research into the use of recycled plastic in the construction sector has gained considerable interest (Alyousef et al. 2021; Agarwal and Gupta 2017). Among various recycled materials, sand-plastic composites have been identified as highly valuable due to their favorable mechanical properties (Iftikhar et al. 2023; Bajracharya et al. 2016). Finite Element Analysis (FEA) has been extensively applied to assess different aspects of sand-plastic construction materials. It has been used to model impact behavior and dynamic compaction of sand, requiring advanced computational techniques to handle large deformations and plastic behavior (PORAN and Rodriguez 1992). FEA has also been employed to analyze axial load transfer in piles, revealing a decrease in shaft strength and an increase in base strength under repeated loading conditions (Altaee et al. 1992). More recent studies have explored the integration of recycled plastic pins (RPPs) with geosynthetics to enhance foundations in loose soils, demonstrating that vertical deformation decreases with increased RPP size and decreased spacing (Azijul Islam et al. 2021). Furthermore, FEA has been used to investigate the dynamic response of sand-filled geocells under impact loads, with results closely matching experimental data and offering insights into the influence of boundary conditions and impact head characteristics (HO and Masuya 2013). While numerous studies have applied FEA to investigate sand-plastic materials, a notable gap remains in the integration and data exchange between design and analysis software platforms. Specifically, interoperability between Rhino known for its advanced design capabilities and Revit commonly used for Building Information Modeling (BIM) is still limited. This study proposes a workflow that facilitates data exchange between Rhino and Revit, aiming to streamline the design-to-analysis process and enhance collaboration in sand-plastic construction research.

2. METHODOLOGY

In our previous work published at the Sigradi 2024 Conference (Estévez 2024), we investigated how architects can use finite element analysis (FEA) to evaluate the behavior of walls constructed from sand-plastic composites. In another study, currently under review for publication, we explored how architects can apply FEA using the Karamba plugin in Grasshopper to analyze sand-plastic construction systems. Building on these findings, this study adopts an applied research approach to develop a workflow that bridges Rhinoceros (Rhino) and Autodesk Revit using Dynamo. The goal is to address the limitations of our previous studies, particularly regarding the lack of interoperability between design and documentation software. This research specifically focuses on architectural elements such as walls, floors, and openings (windows and doors).

Dynamo visual programming was used to automate the generation of Revit models based on Rhino models. Scripts were created in the Dynamo environment and executed via Dynamo Player within Revit, allowing users to run the automation without opening Dynamo each time.

The automated workflow operates in three main steps:

- Level and Floor Creation: The Rhino model is analyzed to extract level information and generate corresponding levels and floors in Revit.
- Wall Generation: Wall geometries from Rhino are analyzed and converted into Revit wall elements.
- Opening Placement: Openings, such as windows and doors, are identified in the Rhino model and recreated in Revit.

]The Revit model is generated using the same coordinate system as the Rhino model to ensure spatial accuracy. For a seamless workflow, the Rhino model must be well-organized. When specific attributes need to be transferred, Rhino object properties can be used in combination with Dynamo's shared parameters to bring this data into Revit. Elements in Rhino should be organized by layers and sublayers to represent different materials and construction types.

For example

Walls (main layer)

- Wall_material_A (sublayer)
- Wall_material_B (sublayer)

Floors (main layer)

- Floor_material_A (sublayer)
- Floor_material_B (sublayer)

2.1. Creation of levels

To create Revit levels using Dynamo, the Revit.Levels node is used, which requires two inputs: elevation and name.

In this workflow, floors were used as reference elements. These floors were initially exported from Rhino as a SAT file and imported into

Dynamo using the Geometry.ImportFromSAT node, with the file path provided as input.

Next, the Geometry.BoundingBox node was used to generate bounding boxes for each floor. From these bounding boxes, the maximum points were extracted, and the Point.Z node was used to retrieve the Z-coordinate (elevation) of each point. These Z-values were then input into the Point.ByCoordinates node to generate point objects. This step was essential to convert the elevation values into point geometry that could be further processed.

To ensure that no duplicate levels were created at the same height, the Point.PruneDuplicates node was used to remove any repeated Z-values. The resulting list of unique elevations was then sorted.

This sorted list served as the elevation input for the Revit.Levels node.

For the name input, the sorted list of elevations was split into two lists:

- One containing value below zero
- One with values equal to or greater than zero

Each list was processed using the Count node to determine the number of levels in each group.

- For the negative elevations, a code block expression "(-n)..(-1)" (where n is the number of items) generated level numbers.
- For positive elevations, the expression "1..(n+1)" was used.

Each set of numbers was then paired with a suffix string using the Concatenate node to generate the final level names.

Finally, to provide greater flexibility when using Dynamo Player, the file path and suffix strings were set as input nodes, allowing users to modify them without editing the script directly. The figure 1 below illustrates the entire process.

Figure 1: Script for level creation

2.2. Creation of floors

To create floors in Revit using Dynamo, the Floor.ByOutlineTypeAndLevel node is commonly used. This node requires three inputs: outline, floor type, and level. All this information was extracted from the SAT file imported from Rhino.

For the outline, as in the previous step, the Brep geometries of the floors were imported using the Geometry.ImportFromSAT node. Then, using the levels created earlier, horizontal planes were generated at each level. These planes were intersected with the Breps using the Geometry.Intersect node, producing intersection surfaces. The Surface.PerimeterCurves node was used to extract the perimeter curves of these surfaces. These curves were then joined using the PolyCurve.ByCurves node, and the resulting polycurves served as the outline input for the Floor.ByOutlineTypeAndLevel node.

For the level input, existing Revit levels were queried using the Categories and All Elements of Category nodes. Then, with the Element.GetParameterValueByName node and “Elevation” as the parameter name, the elevation values of all levels were retrieved. To associate each floor outline with the correct level, a point (typically a corner) was extracted from each polycurve using the PolyCurve.Points node. The Z-values of these points were then obtained using the Point.Z node. To match the number of outlines with the number of levels, the list of elevation values was repeated using the List.OfRepeatedItem node. This repeated list was compared with the list of Z-values from the outlines using a comparison node, resulting in a Boolean mask. This mask was used to dispatch and align each floor outline with its corresponding level based on elevation.

For the floor type input, the Solid.Centroid node was used to find the centroid of each Brep. These centroids were used as origin points to generate vertical planes, which were intersected with the Breps. The Surface.PerimeterCurves node was again used to extract the outline of the resulting intersection surfaces. The Curve.Length node measured the length of each curve, and the List.MinimumItem node was used to determine the shortest length, which corresponds to the floor thickness.

To prevent the creation of multiple floor types with identical thicknesses, duplicates were removed using the Point.PruneDuplicates node. A string prefix for naming the floor types was defined using a String node and combined using the String.Concat node. The ElementType.Duplicate node was then used to duplicate an existing Revit floor type, and the previously generated names were assigned to the new floor types. For defining the material and thickness of each floor type, the Genius Loci package's (Alban 2025) Create Compound System FamilyType node was used. The extracted thickness values were provided as inputs, along with material specifications.

To ensure smooth script operation in Dynamo Player, both the file path and the floor name prefix string were exposed as input nodes, giving users more flexibility and control during execution.

The figure 2 below illustrates the entire process.

Figure 2: Script for floors creation

2.3.Creation of walls

To create walls in Revit using Dynamo, the Wall.ByCurveAndHeight node is used. This node requires four inputs: Curve, Height, Level, and Wall Type.

We began by importing the wall geometries exported from Rhino as a SAT file, using the Geometry.ImportFromSAT node.

For the Curve input, a bounding box was generated for each wall using BoundingBox.ByGeometry. The maximum point of each bounding box was extracted via the BoundingBox.MaxPoint node. Using these maximum points as origins, horizontal planes were created. Each Brep geometry was then intersected with its corresponding plane. The resulting intersection was input into the Surface.PerimeterCurves node to obtain the outline of the intersected plane. By analyzing these perimeter curves with the Curve.PointAtParameter node, we constructed the midline of each geometry, which represents the centerline of the wall. It is important to note that the Curve input in the Wall.ByCurveAndHeight node does not accept PolyCurves; therefore, any polycurves in the list must be exploded into simpler curves.

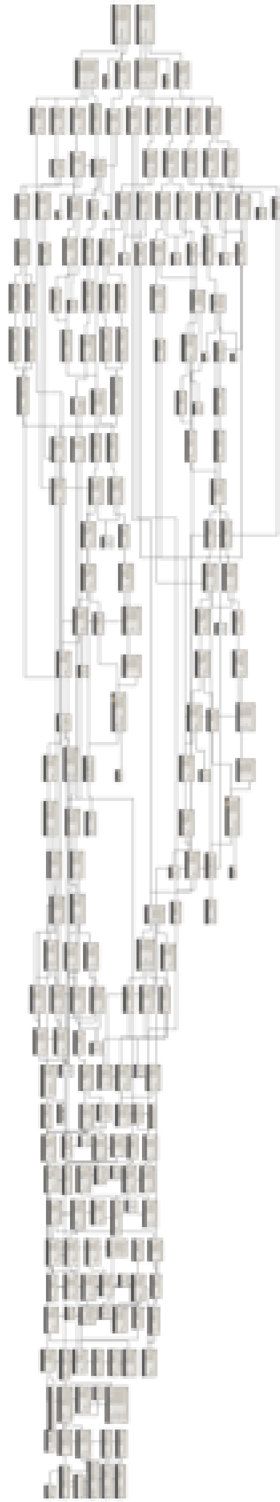
For the Height input, we used the bounding boxes of each geometry to extract the maximum and minimum points via the BoundingBox.MaxPoint and BoundingBox.MinPoint nodes. The Z-coordinates of these points were obtained using the Point.Z node. The height of each wall was then calculated using a code block expression: MaxZ - MinZ.

To assign the Level, we first retrieved all existing levels in the Revit model. This was done using the Categories node (set to Levels), followed by All Elements of Category, and Parameter.ValueByName to extract each level's elevation. By applying a similar method to the one used in the floor creation process, each wall was aligned with the nearest level and assigned a corresponding offset, since walls may not start exactly at the level elevation.

For the Wall Type input, we followed the same procedure used for floors. However, instead of using a floor type in the ElementType.Duplicate node, we selected a wall type.

The figure 3 below illustrates the entire process.

Figure 3: Script for walls creation



2.4. Creation of Openings (Windows and Doors)

To create openings such as windows and doors in Revit using Dynamo, we employed a parametric approach that utilizes the FamilyInstance.ByPoint node from the spring node package (Dimitar 2025). This node requires three main inputs: Host, Type, and Point.

We began by importing the Brep geometries exported from Rhino as a SAT file using the Geometry.ImportFromSAT node. Bounding boxes were then created for each opening geometry using the BoundingBox.ByGeometry node. These bounding boxes were converted into cuboids via the BoundingBox.ToCuboid node. This allowed us to extract geometric properties such as width, length, and height using the Cuboid.Width, Cuboid.Length, and Cuboid.Height nodes.

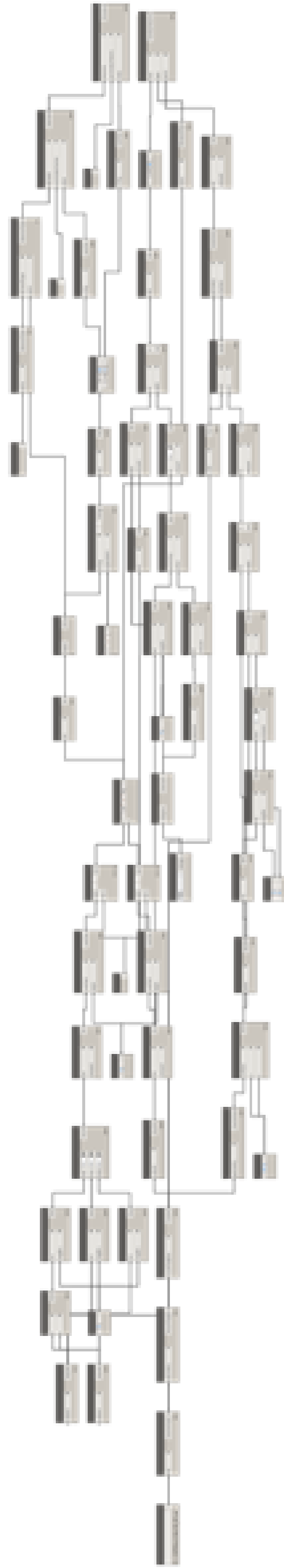
In our setup, the width and length represented the wall thickness and the opening width, respectively. To automate the selection of the correct width for the opening, we compared the Cuboid.Width and Cuboid.Length values, producing a Boolean list. This list was used as an input to the If node to determine the actual width of the opening. The height was directly taken from the Cuboid.Height node output. To generate appropriate family types, we used the String.Concat node to name each opening instance in the format W×H, where W is width and H is height. We then selected the relevant family type in Revit using the ElementType.ByName node, and duplicated it using ElementType.Duplicate, assigning it the custom name. The Element.SetParameterByName node was used to assign specific width and height values to each duplicated family type.

For the Host input, we queried all wall elements in the Revit model using the Categories and All Elements of Category nodes. The geometries of the openings were intersected with those of the walls using a cross-product lacing method. This ensured that each opening would be matched with its corresponding host wall. The intersection results (Boolean list) were used to assign each opening to the correct wall element.

The Point input refers to the insertion point of the opening. To define it, we extracted the bottom surface of each opening's bounding box. Then, using the Surface.PointAtParameter node with U and V parameters set to 0.5, we located the center point on this bottom face. This point was used as the placement location for the window or door instance in Revit.

The figure 4 below illustrates the entire process.

Figure 4: Script for openings creation



3. CASE STUDY AND DISCUSSION

To evaluate the effectiveness of the developed script, a test was conducted on a case study building model containing approximately 324 Breps. As previously mentioned, all elements were carefully organized in Rhino according to the workflow requirements. In addition to simple geometry, a circular wall was intentionally included in the Rhino model to test the script's ability to handle complex, non-linear shapes. This allowed us to assess both the robustness and versatility of the workflow.

The Revit model was generated using Dynamo Player within Revit, which provided a user-friendly interface for executing the preconfigured scripts. The following sequence was followed:

- Creation of Revit levels
- Generation of floors
- Construction of walls
- Insertion of openings (doors and windows)

Each component was successfully created, and the entire model was generated in just a few seconds. This runtime reflects the processing time required by Dynamo to compute and execute the scripts.

- Figure 5 shows the Rhino model used in this study.
- Figure 6 illustrates the workflow as executed using Dynamo Player in Revit.
- Figure 7 displays the final Revit model generated from the Rhino geometry.

Figure 5: Rhino model

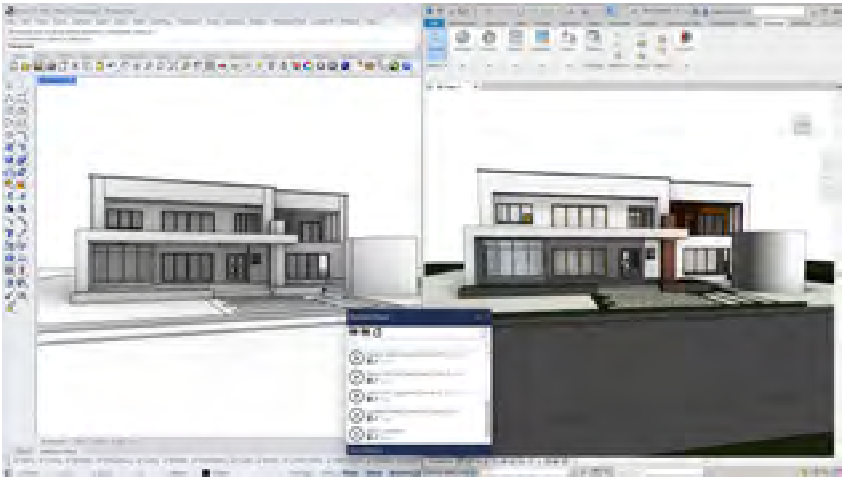


Figure 6: Interoperability between Rhino and Revit.

Figure 7: Revit model

The accuracy of the generated Revit model indicates that the proposed workflow has significant potential to enhance interoperability between Rhino and Revit. By automating the transfer of architectural elements through Dynamo, the workflow demonstrates a practical and efficient approach to bridging the gap between these two platforms.

However, there are several limitations in the current version of the script that must be addressed. In this study, it was assumed that all walls and floors share the same material, which limits the workflow's flexibility for more complex or heterogeneous architectural designs. While this limitation can be partially resolved by organizing elements into sublayers within Rhino (e.g., grouping elements by material), future research will focus on addressing this issue directly within Dynamo, allowing for more dynamic material assignment and less manual preprocessing. Additionally, the current script is limited to walls that curve in a single direction. At this stage, double-curved (i.e., doubly curved or freeform) wall geometries are not supported. Future development will involve extending the script's capabilities to handle more complex geometries and improving its adaptability to a wider range of architectural forms. Overall, the workflow presents a strong foundation for Rhino–Revit interoperability, and continued refinement will aim to expand its applicability and performance in real-world architectural projects.

4. CONCLUSION

This research proposed and tested a streamlined workflow to enhance interoperability between Rhino and Revit using Dynamo visual programming. Building upon previous work involving finite element analysis and performance evaluation of sand plastic composite structures, this study addressed a key limitation data transfer and model reconstruction between Rhino and Revit. By developing a set of Dynamo scripts, the study demonstrated a method for automating the generation of architectural elements such as levels, floors, walls, and openings based on Rhino geometry. The workflow was tested on a detailed case study involving over 300 Breps, including both linear and curved elements. Results showed that the proposed approach can successfully and efficiently generate a Revit model from a well-organized Rhino file in a matter of seconds, demonstrating both accuracy and time efficiency. Despite its success, the current implementation includes some limitations. All elements were assigned uniform materials, and the script could only process walls with single-direction curvature. Future work will focus on improving material differentiation within Dynamo and expanding the script's ability to handle double-curved geometries, further increasing its applicability to complex architectural forms. Ultimately, this workflow contributes to bridging the interoperability gap between design and documentation tools, offering architects and designers a practical method for integrating Rhino's modeling flexibility with Revit's BIM capabilities.

REFERENCES

Agarwal, S. and Gupta, R.K. (2017) "Plastics in Buildings and Construction", in Applied Plastics Engineering Handbook: Elsevier, pp. 635–649.

Alban, d.C. (2025) GitHub - albandechasteigner/GeniusLociForDynamo, 30 April. Available at: https://github.com/albandechasteigner/GeniusLociForDynamo (Accessed: 30 April 2025).

Altaee, A., Evgin, E. and Fellenius, B. (1992) 'Axial load transfer for piles in sand. II. Numerical analysis', Canadian Geotechnical Journal. doi: 10.1139/t92-003

Alyousef, R. et al. (2021) "Potential use of recycled plastic and rubber aggregate in cementitious materials for sustainable construction: A review", Journal of Cleaner Production, 329, p. 129736. doi: 10.1016/j.jclepro.2021.129736

Azijul Islam, M. et al. (2021)" Numerical Modeling of Recycled Plastic Pin Reinforced Embankment over Soft Soils": American Society of Civil Engineers.

Bajracharya, R.M. et al. (2016) "Characterisation of recycled mixed plastic solid wastes: Coupon and full-scale investigation", Waste Management (New York, N.Y.), 48, pp. 72–80. doi: 10.1016/j.wasman.2015.11.017

Dimitar, V. (2025) GitHub - dimven/SpringNodes: A collection of Dynamo nodes, 30 April. Available at: https://github.com/dimven/SpringNodes (Accessed: 30 April 2025).

Estévez, A.T. (2024) SIGraDi 2024: XXVIII International Conference of the Ibero-American Society of Digital Graphics: Institute for Biodigital Architecture & Genetics. Available at: https://books.google.cz/books?id=OhEq0QEACAAJ.

HO, T.S. and Masuya, H. (2013) 'Finite element analysis of the dynamic behavior of sand-filled geocells subjected to impact load by rockfall', International Journal of Erosion Control Engineering, 6(1), pp. 1–12. doi: 10.13101/ijece.6.1

Iftikhar, B. et al. (2023) 'Experimental study on the eco-friendly plastic-sand paver blocks by utilising plastic waste and basalt fibers', Heliyon, 9(6), e17107. doi: 10.1016/j.heliyon.2023.e17107

Lavkush et al. (2024) 'Effect of microplastics pollution in riverine ecosystem: A review', Emergent Life Sciences Research, 10(02), pp. 15–31. doi: 10.31783/ELSR.2024.1021531

Poran, C. and Rodriguez, J.A. (1992) 'Finite element analysis of impact behavior of sand', SOILS and FOUNDATIONS, 32(4), pp. 68–80. doi: 10.3208/sandf1972.32.4_68

BLENDED LEARNING STRATEGIES IN ARCHITECTURAL EDUCATION: CAD PEDAGOGIES FOR DESIGN INNOVATION.

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ABSTRACT:

The integration of digital tools into architectural design has significantly transformed design education, necessitating pedagogical approaches that combine technical proficiency with creative problem-solving. This study presents a blended learning (BL) framework, enhanced with problem-based learning (PBL), for teaching computer-aided design (CAD) and related digital tools in architectural education. The research responds to challenges in simultaneously acquiring technical skills and engaging in creative design tasks, which often overwhelm students when relying solely on studio-based instruction or unstructured online tutorials. By combining structured modules with self-directed learning, the model

aims to bridge virtual and physical learning environments while promoting student autonomy and reflective design thinking.

The paper introduces a six-module methodology implemented in the Computer Applications in Architecture (CAA) course at Gebze Technical University. The course structure progresses from foundational tools (AutoCAD, SketchUp, and Photoshop) to advanced techniques (Rhino, Grasshopper, 3D printing, and Building Information Modeling), aligning each module with problem-based tasks. A flipped classroom model was adopted, combining asynchronous pre-recorded instructional materials with synchronous studio sessions, allowing students to learn at their own pace while benefiting from in-person workshops, peer collaboration, and guided feedback. The course design also addressed institutional factors, including the absence of other mandatory CAD courses and large class sizes, which made BL a practical solution for balancing instructional efficiency with individual learning needs.

Evaluation of the model was conducted through student surveys and analysis of coursework outcomes. Survey results indicated high levels of satisfaction with in-class exercises, Q&A sessions, and the overall blended structure, with students reporting significant improvements in both technical competencies and design capabilities. However, feedback also highlighted challenges, including the heavy workload and the need for shorter, more concise instructional videos.

The findings demonstrate that a structured BL–PBL framework can effectively integrate digital tool instruction with design-oriented learning, enabling students to develop adaptable digital skills relevant to evolving professional demands. The study emphasizes that purpose-driven tool use, rather than tool-specific training, fosters deeper learning and transferable competencies. It concludes by proposing recommendations for future implementations, including optimizing video lengths, balancing workloads, and contextualizing modules to align with institutional priorities. The presented framework serves as a replicable model for architectural programs seeking to enhance digital design education while maintaining the pedagogical values of studio-based learning.

Keywords: Blended Learning (BL), Computer-Aided Design (CAD) Education, Problem-Based Learning (PBL), Parametric Design and BIM, Architectural Pedagogy

1. INTRODUCTION

Since the introduction of digital tools into architectural design, a range of theories has emerged illustrating their capacity to enhance creativity, materialize conceptual ideas, and support analytical thinking within the design process (Oxman, 2006; Herr and Kvan, 2007; Özkar, 2011). The recognition of these tools' transformative impact has prompted critical discussions on how best to integrate them into architectural education.

Traditionally, architectural education has been anchored in studio-based learning, where experiential engagement plays a central role. While some pedagogical approaches advocate for the development of digital proficiency within the studio environment (Iordanova, 2007; Oxman, 2017), studies suggest that simultaneously mastering digital tools and generating creative outputs can pose significant challenges for students (Ibrahim & Pour Rahimian, 2010; Soliman et al., 2019).

Consequently, the inclusion of dedicated Computer-Aided Design (CAD) instruction within the architectural curriculum has gained increasing importance (Duarte et al., 2012). With the emergence of state-of-the-art technologies such as artificial intelligence systems, determining how to effectively embed these technological tools into architectural curricula has become even more crucial. For this reason, equipping students with CAD, digital fabrication, and AI-related skills outside the studio—yet aligned with studio learning—has become increasingly important.

This raises critical questions: How can a CAD course be constructively aligned to support student learning? How might cutting-edge technologies be effectively integrated? And which pedagogical strategies best optimize CAD education in architectural education while teaching CAD to also enhance design thinking?

Amid this discourse—particularly during the Covid-19 pandemic--induced shift to remote education—blended learning (BL) has emerged as a compelling pedagogical model (Garrison and Vaughan, 2008). Increasingly implemented alongside face-to-face instruction, BL enriches architectural education by creating flexible and responsive learning environments. When combined with problem-based learning strategies, these models offer promising pathways for teaching CAD in architecture (Eilouti, 2007; Ulger, 2018).

Within this context, the present study investigates these pedagogical frameworks and evaluates their influence on CAD education. Focusing on the application of BL in the teaching of computer-aided design, parametric modeling, and digital fabrication, this research underscores the potential of blended methodologies to bridge the gap between physical and virtual learning environments.

The central hypothesis of the study is that blended learning methods can establish a bridge between virtual and physical settings, breaking the dominance of centralized, instructor-led learning in the CAD classroom and offering students alternative learning strategies. Another key argument of the hypothesis is that while providing alternative pathways, the learning process should also ensure that students follow a structured and regulated progression. Such structured guidance is essential for efficiently teaching the tools students will use, particularly as they often become lost in the vast array of unstructured online tutorials.

Thus, the primary aim of this study is to foster students' skill development efficiently by building a bridge between virtual and physical environments through BL, while simultaneously adopting a problem-based model that aligns with the structure of the formal curriculum. Ultimately, the study argues that such methods enable students to acquire fundamental knowledge of a broader range of technical tools, thereby providing significant support for their professional development.

As a case study, the paper introduces a syllabus framework for the Computer Applications in Architecture course at Gebze Technical University's Department of Architecture. The curriculum adopts a phased structure—Drafting, Basic Modeling, Post-Production, Advanced Modeling, and Building Information Modeling (BIM)—delivered sequentially throughout the semester and supported by assignments, individual projects, and collaborative group work.

This paper argues that a well-structured, problem-based blended learning framework—seamlessly integrating digital tool proficiency with conventional pedagogical foundations—can significantly enhance students' engagement with diverse digital techniques, improve their digital capabilities and literacy, and enable them to become more adept at learning emerging tools. The study advocates for the development of future architects who can navigate the increasing complexities of contemporary design practice by adopting innovative methods focused on digital skill acquisition. The following section elaborates on the relevant literature and methodology that inform the design of this pedagogical model.

2. BACKGROUND AND THEORY

As in many other fields of education, a variety of blended learning (BL) strategies have recently been proposed for architectural education. Research findings indicate that the implementation of BL strategies—by enabling effective communication, access to resources, maintaining peer connections, and facilitating group work—has a positive influence on the outcomes of architectural design studios (Iranmanesh & Onur, 2022).

Particularly in establishing effective communication, ensuring access to suitable resources, and supporting collaborative work, cloud-based tools have been shown to provide substantial benefits (Al-Samarraie & Saeed, 2018). Synchronous webinars and virtual reality (VR) technologies can enrich learning through authentic experiences, such as demonstrations and virtual visits, increasing engagement and supporting skill development (Nortvig et al., 2020). However, technology must be integrated in an appropriate and effective manner to achieve these benefits (Megahed & Hassan, 2022).

According to Megahed and Hassan (2022), most BL approaches can be categorized into four main integration models:

- Rotation Model: Students rotate between different learning modalities, including face-to-face studio and online learning.
- Flex Model: Curriculum is mostly online, with teachers providing support as needed.
- Self-Blend Model: Students take additional online courses to supplement traditional instruction.
- Enriched Virtual Model: Combines required face-to-face sessions with substantial online coursework, giving students control over time, place, and pace of learning.

Among these, the enriched virtual model is regarded as the most suitable for CAD courses, as it balances online autonomy with essential face-to-face interaction. In this setting, instructors act as facilitators while students are encouraged to engage in self-directed learning (Alnusairat et al., 2020).

To establish an optimal BL framework, structured pathways are essential. In CAD education, the absence of structure can lead to confusion due to unstructured information sources (Kolarevic, 2016). Therefore, organized instructional sessions and the integration of Problem-Based Learning (PBL) become critical.

PBL structures the learning process around real-world problems and builds on experiential learning theories (De Graaf & Kolmos, 2003; Schön, 1984). It connects theoretical design knowledge with practice, fostering abstraction, creativity, and critical thinking. Architectural education is inherently suited to PBL, as design processes are complex, collaborative, and problem-centered (Bridges, 2006; Eilouti, 2007). When technical tools are taught within this framework, students better understand their creative potential (Demirbaş & Demirkan, 2003).

The integration of BL with PBL in the proposed model serves two primary goals:

- Ensuring engagement in a problem-focused process while allowing self-paced learning.
- Prioritizing design thinking and functional tool use over tool-specific commands.

Modules were designed to introduce tools as means of accomplishing tasks rather than ends in themselves. Students sometimes solved the same problem using different tools, understanding that while tools may change, design principles remain central. This approach shifts learning from teacher-centered to student-centered, promoting meaningful interaction, trial-and-error, and continuous feedback.

3. MODEL

The model was designed to equip students with digital skills and foster their creativity and reflective thinking, preparing them to address complex future problems, while also reflecting the specific context of the course at Gebze Technical University (GTU). The study argues that future implementations following a similar methodology should adapt the course content and modules to their own institutional and pedagogical contexts, ensuring relevance to their particular educational environment. In the following section, the original context in which the course was implemented will be presented.

3.1. Course context – why is the curriculum so dense?

The Computer Applications in Architecture (CAA) course at GTU was designed to balance the development of students' technical proficiency with the cultivation of their creative and reflective capacities within architectural education. The course adopts a blended learning (BL) model that integrates problem-based tasks with the sequential introduction of digital tools.

GTU offers no single dominant pedagogical approach; rather, multiple teaching methods coexist. Depending on the instructors' strategies, students are expected to master a wide range of digital and manual design media across various courses. This diversity necessitates early familiarity with digital tools.

In the first semester, students focus on manual techniques and creativity-focused studios. The CAA course, offered in the second semester, bridges foundational design skills and digital competencies required in later stages. By the end of the course, students are expected to have acquired baseline knowledge of several digital tools, enabling informed tool selection in advanced courses.

Since there is no other mandatory CAD course in the curriculum, the 14-week course is structured to cover the most valuable digital design media for students' future education and professional development. While elective digital courses are offered later, the introduction to parametric design and digital manufacturing in this course provides a foundation for further learning. Each term, one Building Information Modeling (BIM) platform—Revit or ArchiCAD—is introduced, knowledge that is reinforced in subsequent studios.

Another factor shaping the dense structure is the large number of students enrolled. The course is offered to all first-year students, often resulting in class sizes of around 100. This presents challenges for classroom management and personalized learning. The blended learning model addresses these challenges by combining asynchronous tutorials with synchronous studio time, allowing students to progress at their own pace while benefiting from hands-on learning and group discussions.

The next section details the application of the blended learning strategy and the seven-module structure that facilitated problem-based learning.

3.2. Blended learning – methodological approach influenced by the legacy of the distance learning period

The primary objective of the course was not only to ensure that students gained technical proficiency in digital tools but also to enable them to use these tools creatively to solve architectural problems. To achieve this, the course was structured in modules and comined both synchronous and asynchronous modalities.

For the online components, an institutional collaboration platform was used for material sharing, live sessions when required, and assignment submissions. Over a 14-week semester, the course was organized into seven modules. Each module focused on a specific skill, either through training on a particular tool or by introducing a broader competence, such as digital manufacturing.

Each submodule followed two possible formats:

- Asynchronous online instruction session followed by a face-to-face studio Q&A and workshop session. (Figure 1)
- Synchronous online instruction session followed by a face-to-face studio Q&A and workshop session.

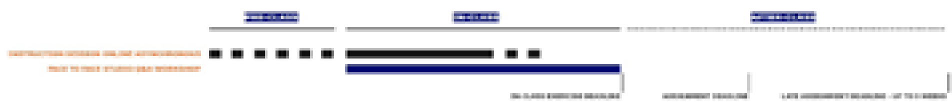

Figure 1: The diagram presents the weekly structure of course delivery.

Both asynchronous and synchronous sessions provided students with the necessary preparatory materials to acquire foundational knowledge before the in-person classes. These materials included pre-recorded lectures—sometimes created during a live session and reused in subsequent years—or existing recorded tutorials, along with assigned readings and short exercises. When pre-recorded material was provided, students were expected to review it in advance and complete the in-class exercises (ICE) during the face-to-face session (Figure 2).

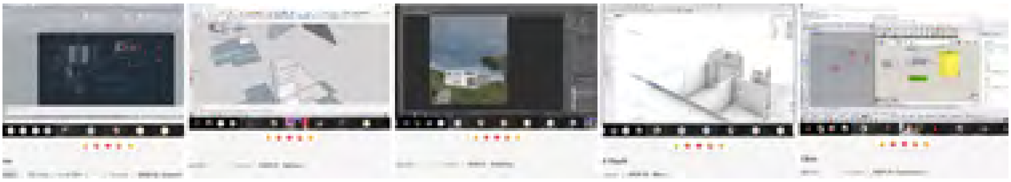

Figure 2: Sample scenes from pre-recorded instructional sessions.

Each module typically lasted two weeks, and this structure—pre--class preparation followed by in-class application—was repeated weekly. At the end of each module, students were given an assignment, to be submitted within three weeks, to consolidate their learning. Students who had completed the exercises during the face-to-face workshops could move directly to the assignment stage. When a recorded session was unavailable or a new submodule was introduced, the first instructional session was delivered live online, followed by time to complete exercises before the subsequent in-person session focused on assignments.

Figure 3: Classroom layouts based on module requirements.

Thus, a flipped classroom model was adopted. Pre-class video recordings facilitated advance preparation and remained accessible during face-to-face sessions. Students could review the recordings at their own pace and revisit them when needed, enabling both independent work and peer collaboration. Instead of relying on a single instructor-led demonstration projected on a large screen, students engaged with the material individually on their own devices, seeking assistance from the instructor or peers as necessary. The classroom layout was also adjusted each week according to the specific requirements of each module (Figure 3).

This approach aligns with an enriched virtual model, which incorporates the key features of BL by combining various pedagogical approaches, learning styles, delivery modes, and teaching methods (Megahed & Hassan, 2022). It fosters interaction by integrating face-to-face learning with online tools—especially during synchronous sessions where platforms such as Mural or Miro were used to enhance participation. The model also provides flexibility, allowing students to control the time, place, and pace of their learning, extending learning beyond in-class hours.

This flexibility supports both synchronous (real-time) and asynchronous (self-paced) learning, ensuring that students can progress through the modules at their own pace. In-person sessions targeted higher-order cognitive skills, emphasizing collaborative problem-solving, peer discussions, and hands-on workshops. Within this structure, the instructor acted as a facilitator, providing guidance, feedback, and resources while encouraging students to take greater responsibility for their own learning.

3.3. Content - various aspects of design and technology

Introducing new software tools into an educational curriculum enriches learning by providing advanced opportunities, aligning coursework with industry trends, fostering interdisciplinary collaboration, and enhancing critical skills. However, their primary purpose should be to manage the growing volume of information, organize knowledge, and use it effectively in problem-solving. Only under these conditions can new tools contribute meaningfully to critical thinking and problem-solving skills.

PBL and self-directed learning are therefore crucial for teaching software tools (Wood, 2003). In architectural education, where tools support design processes, adopting a design-thinking-oriented, problem--based approach rather than a purely tool-focused one is essential.

Accordingly, in designing the CAA course, the focus was not on teaching the most popular tools but on selecting those that best enhance students' design processes. As stated in Section 3.1, GTU students are expected to develop a broad range of skills throughout their education. When the right tools are selected, knowledge gained in this course can be reinforced in later years, preparing students to enter professional practice as competent designers.

Based on these considerations, the course content was structured around three primary objectives, each supported by dedicated modules:

- **Enabling students to complete a design process from start to finish using simple digital tools:**

Students should be able to produce conceptual sketch models in a digital environment without requiring complex inputs, convert these into accurate drawings, and present their designs effectively. To achieve this, the first three modules—Drafting, Basic Modeling, and Post-Production & Board Design—were designed to support these goals.

- Drafting: AutoCAD for 2D drafting
- Basic Modeling: SketchUp for 3D modeling
- Post-Production: Photoshop for visualization and board design techniques

At the time of this study, AI-assisted tools for post-production and rendering were not yet part of the course. However, in subsequent years, AI-based tools have been integrated as an additional module.

These three modules culminate in the mid-term project, in which students draft, model, and visualize a single-family house design. Each module builds on the previous one: in the Drafting module, students create the floor plans; in Basic Modeling, they develop a geometric 3D model using additional reference drawings and visuals; and in post-production, they prepare a presentation board of the design using rendered views from their model.

- **Introducing advanced modeling, parametric design, and digital fabrication techniques:**

The fourth and fifth modules provide students with exposure to advanced digital design tools:

- Advanced Modeling: Rhino and Grasshopper for parametric modeling
- Manufacturing: 3D printing for fabrication techniques

Although these modules do not aim to teach all advanced functionalities in depth, they introduce students to the fundamentals of parametric modeling and computational design thinking. This exposure creates opportunities for talented and motivated students to further develop these skills in elective courses and advanced design studios offered in later years.

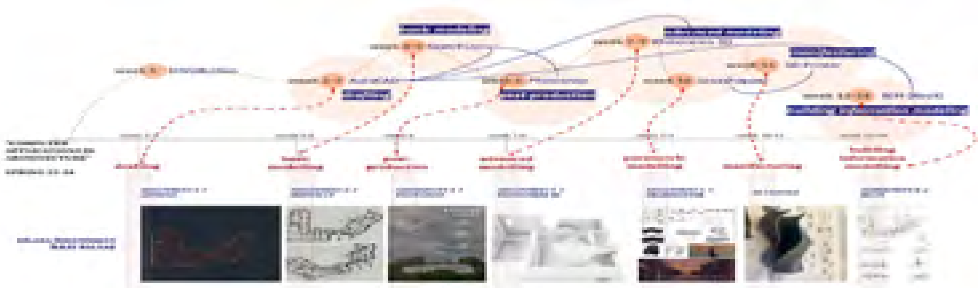

Figure 4: Module structure with corresponding outputs.

The manufacturing module supports students' understanding of form by enabling them to prepare their models for digital fabrication and 3D printing. Working in groups, students learn through peer collaboration how to optimize their models for fabrication and gain hands-on experience with 3D printing. These modules emphasize that Rhino and Grasshopper are not merely representational tools but interactive design environments, enabling students to distinguish between basic digital modeling and generative, parametric design approaches (Oxman, 2008). For this reason, the exercises in these modules also include explorations of experimental forms alongside conventional ones.

- **Familiarizing students with information modeling (BIM)**

The final module introduces students to Building Information Modeling (BIM) and its significance in contemporary architectural practice. Beyond geometric modeling, students learn the principles of semantic modeling and the concept of design realization.

BIM education in architecture often faces cultural resistance due to concerns that it might limit students' critical and creative thinking. As a result, BIM concepts and platforms are frequently excluded from design-focused CAD courses (Denzer & Hedges, 2008). However, the increasing technological complexity of buildings and the need for collaborative, multi-disciplinary workflows make BIM proficiency essential for future architects.

In this module, BIM is introduced as a design-realization environment. For the year in which this study was conducted, Autodesk Revit was selected as the BIM platform due to the availability of free student licenses. For other software, trial versions were sufficient for the two-week module. Students who wished to continue using these tools beyond the course were responsible for acquiring licenses independently.

Consequently, the course was organized into seven modules, closely interlinked to create a coherent, problem-based workflow (Figure 4):

- Drafting – AutoCAD (2D drafting)
- Basic Modeling – SketchUp (3D modeling)
- Post-Production – Photoshop (visualization and board design)
- Advanced Modeling – Rhino
- Parametric Modeling - Grasshopper
- Manufacturing – 3D printing (digital fabrication)
- Building Information Modeling – Revit (BIM introduction)

Each module followed a two-week structure. In the first week, students were introduced to the essential commands and techniques of the software. In the second week, they completed a problem-based exercise during class. Subsequently, they were given an assignment similar to the exercise, to be submitted within three weeks.

To maintain continuity and avoid disengagement, the first three modules and the BIM module (Module 6) were designed to be strictly interconnected. For example, the single-family house introduced in Module 1 is consistently developed across Modules 2 and 3, and later re-created in BIM for the final project.

Following the mid-term, the fourth and fifth modules focused on advanced and parametric design tools, as well as digital fabrication. Assignments in these modules emphasized group work and collaborative problem-solving, supported by tutorial videos and online resources. This approach encouraged brainstorming and peer learning, helping students understand computational design thinking and develop algorithmic and parametric reasoning skills (Vrouwe et al., 2020). Students fabricated their final models using 3D printing.

The next section will present examples of student work to illustrate how the course structure was implemented in practice. The effectiveness of the model was evaluated through surveys, the results of which are discussed in the subsequent section.

4. RESULTS

4.1. Student works

Figure 5 presents examples of student work produced during the Computer Applications in Architecture (Spring 2023–2024) course. Students worked in pairs, addressing the same design problem across different assignments, each focusing on a specific digital tool. This iterative workflow enabled students to understand how the same architectural task can be approached using various software platforms, fostering a comparative understanding of their capabilities.

- Drafting (AutoCAD): Students began by producing precise 2D drawings of the given design problem, emphasizing accuracy and construction detailing.

- Basic Modelling (SketchUp): The same project was then developed as a simple 3D model, introducing volumetric thinking and spatial organization.
- Post-Production (Photoshop): Rendered outputs from SketchUp were enhanced in Photoshop, where students learned visualization and presentation techniques.
- Building Information Modelling (Revit): The design was subsequently developed in Revit, enabling students to engage with semantic and data-driven aspects of BIM.

A parallel set of assignments involved a different design task:

- Advanced Modelling (Rhino): Students experimented with complex geometries and surface manipulations.
- Parametric Modelling (Grasshopper): The Rhino models were further explored through parametric logics, encouraging algorithmic design thinking.
- Manufacturing (3D Printing): Selected Grasshopper outputs were fabricated using 3D printers, linking digital modelling with physical production.

Figure 5: Examples of student work for each module.

This progressive structure exposed students to a wide range of tools and workflows while demonstrating how a single design problem can evolve across different platforms. In general, the student work was found to be highly successful, and the majority of students were observed to be actively engaged throughout the course. The tasks resulted in advanced outputs that met expectations.

When the products are reviewed horizontally across the semester, it is evident that students successfully completed assignments of varying complexity. Viewed vertically, students at different performance levels were able to accomplish comparable tasks with similar success. Out of the 114 enrolled students, 6 withdrew from the course, 21 did not meet the requirements and failed, 14 achieved full marks, 29 obtained the second-highest grade, and the remaining students completed the course with intermediate scores.

While achieving these results, students' opinions on the course were gathered through a comprehensive survey. The findings of this survey are presented in the following section.

4.2. Survey Results

At the end of the semester, a student survey was conducted to evaluate the effectiveness of the Computer Applications in Architecture course. The findings, supported by visual data, highlight both the strengths of the course and areas for further refinement.

The survey results indicate that students experienced a marked improvement in both technical knowledge and design skills. The statement "This course improved my knowledge and skills in using computers in the field of architecture" received an average score of 4.26/5, with 54 students giving the highest rating. Similarly, the perceived impact on design capabilities was also positive, with an average score of 3.97/5, confirming that even though the course primarily focused on digital tools, students also experienced parallel gains in creative design thinking (Figure 6).

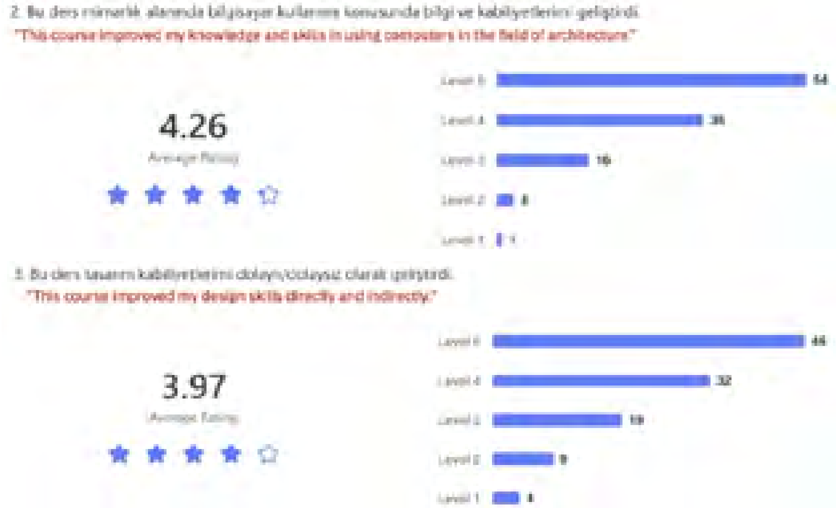

Figure 6: Results of the survey.

In-class exercises and Q&A sessions:

As shown in the first chart, in-class exercises (ICE) were rated positively, with an average score of 4.03/5. Although students described them as demanding, they valued their role in consolidating knowledge. Q&A sessions received one of the highest ratings (4.30/5), being highlighted as essential for clarifying complex topics and deepening understanding.

Blended learning experience:

The blended structure—combining asynchronous videos with in-person sessions—received an average rating of 3.99/5. Students appreciated the flexibility of recordings, which reduced anxiety and improved preparedness, but emphasized that face-to-face interaction was crucial for feedback. Several suggested that shorter video segments would enhance engagement.

Course structure and workload:

The phased methodology, progressing from AutoCAD to SketchUp, Photoshop, and Revit, alongside Rhino, Grasshopper, and 3D printing, was regarded as logical and beneficial. This structure clarified how a single design problem evolves across different platforms. However, ICEs and assignments were described as intensive, though students acknowledged the workload as valuable for gaining proficiency.

Overall, ratings clustered around Levels 4 and 5, confirming a positive perception of the course. The highest satisfaction was linked to Q&A sessions and improved knowledge, while lower ratings reflected the heavy workload and long videos. These findings confirm that the BL model created a student-centered learning environment, integrating technical proficiency with collaborative and problem-based learning, while indicating that optimizing video lengths and balancing workload could further improve the course.

5. DISCUSSION AND CONCLUSION

The findings highlight the potential of blended learning (BL) combined with problem-based learning (PBL) to address the challenges of teaching computer-aided design (CAD) in architectural education. The phased structure of the Computer Applications in Architecture (CAA) course allowed students to gradually acquire technical skills while solving real-world design problems. Through a flipped classroom approach integrating asynchronous materials with in-person sessions, students gained greater control over their learning pace. Survey results showed that students valued this flexibility and reported improvements in both technical proficiency and design thinking.

However, several challenges emerged. The intensive workload, including in-class exercises (ICEs) and assignments, was described as demanding. While students acknowledged its value for skill development, feedback suggests that future iterations could benefit from workload adjustments and shorter videos to enhance focus. The findings also reaffirm that face-to-face interaction is crucial for feedback, peer discussions, and collaborative problem-solving, elements central to architectural education's studio tradition.

This study supports previous research emphasizing that BL approaches must be tailored to institutional contexts (Megahed & Hassan, 2022). The CAA course was shaped by GTU's pedagogical diversity and the absence of other mandatory CAD courses, ensuring early exposure to key digital tools, parametric design, and BIM. This aligns with the broader shift from teacher-centered instruction to facilitator-guided, student-centered learning, encouraging self-directed exploration and adaptability—skills increasingly critical for future architects.

Overall, the study demonstrates that a structured BL framework combined with PBL effectively bridges traditional studio pedagogy and the technical demands of CAD education. The CAA course successfully integrated drafting, modeling, visualization, parametric design, digital fabrication, and BIM within a phased curriculum. Survey results confirmed significant benefits, particularly in technical skill acquisition and confidence in using digital tools.

While feedback was largely positive, reducing video lengths, balancing workloads, and maintaining meaningful in-person interaction could further enhance learning. Focusing on purpose-driven tool use rather than tool-specific training ensures that students develop adaptable digital skills aligned with industry demands. This study contributes to discussions on BL and PBL in architectural education by offering a replicable framework combining flexibility, structured progression, and real-world problem-solving, adaptable to different institutional contexts.

REFERENCES

Al-Samarraie, H. and Saeed, N. 2018. A systematic review of cloud computing tools for collaborative learning: Opportunities and challenges to the blended-learning environment. Computers & Education, 124, pp. 77–91. Available at: https://doi.org/10.1016/j.compedu.2018.05.016

Alnusairat, S., al Maani, D. and Al-Jokhadar, A. 2020. Architecture students' satisfaction with and perceptions of online design studios during COVID-19 lockdown: the case of Jordan universities. Archnet-IJAR: International Journal of Architectural Research, 15(1), pp. 219–236. Available at: https://doi.org/10.1108/ARCH-09-2020-0195

Alymani, A. 2024. Integrating Artificial Intelligence Rendering Tools in Design: Integrating AI as teaching methods in architectural education. pp. 629–638. Available at: https://doi.org/10.52842/conf.ecaade.2024.2.629

Banihashem, S.K., Noroozi, O., den Brok, P., Biemans, H.J.A. and Kerman, N.T. 2023. Modeling teachers' and students' attitudes, emotions, and perceptions in blended education: Towards post-pandemic education. The International Journal of Management Education, 21(2), p.100803. Available at: https://doi.org/10.1016/j.ijme.2023.100803

Bridges, A. 2006. A Critical Review of Problem Based Learning in Architectural Education. pp. 182–189. Available at: https://doi.org/10.52842/conf.ecaade.2006.182

De Graaf, E. and Kolmos, A. 2003. Characteristics of problem-based learning. International Journal of Engineering Education, 19(5), pp. 657–662.

Demirbaş, O.O. and Demirkan, H. 2003. Focus on architectural design process through learning styles. Design Studies, 24(5), pp. 437–456. Available at: https://doi.org/10.1016/S0142-694X(03)00013-9

Denzer, A.S. and Hedges, K.E. 2008. From CAD to BIM: Educational Strategies for the Coming Paradigm Shift. AEI 2008, pp. 1–11. Available at: https://doi.org/10.1061/41002(328)6

Duarte, J.P., Celani, G. and Pupo, R. 2012. Inserting Computational Technologies in Architectural Curricula. In: Computational Design Methods and Technologies, pp. 390–411. IGI Global. Available at: https://doi.org/10.4018/978-1-61350-180-1.ch022

Eilouti, B. 2007. A problem-based learning project for computer-supported architectural design pedagogy. Art, Design & Communication in Higher Education, 5(3), pp. 197–212. Available at: https://doi.org/10.1386/adch.5.3.197_1

Garrison, D.R. and Vaughan, N.D. 2008. Blended learning in higher education: Framework, principles, and guidelines. John Wiley & Sons.

Herr, C.M. and Kvan, T. 2007. Adapting cellular automata to support the architectural design process. Automation in Construction, 16(1), pp. 61–69. Available at: https://doi.org/10.1016/j.autcon.2005.10.005

Ibrahim, R. and Pour Rahimian, F. 2010. Comparison of CAD and manual sketching tools for teaching architectural design. Automation in Construction, 19(8), pp. 978–987. Available at: https://doi.org/10.1016/j.autcon.2010.09.003

Iordanova, I. 2007. Teaching Digital Design Exploration: Form Follows…. International Journal of Architectural Computing, 5(4), pp. 685–702. Available at: https://doi.org/10.1260/147807707783600807

Iranmanesh, A. and Onur, Z. 2021. Mandatory Virtual Design Studio for All: Exploring the Transformations of Architectural Education amidst the Global Pandemic. International Journal of Art & Design Education, 40(1), pp. 251–267. Available at: https://doi.org/10.1111/jade.12350

Kolarevic, B. 2016. Simplexity (and Complicity) in Architecture. pp. 25–31. Available at: https://doi.org/10.52842/conf.ecaade.2016.1.025

Megahed, N. and Ghoneim, E. 2022. Blended Learning. International Journal of Mobile and Blended Learning, 14(1), pp. 1–16. Available at: https://doi.org/10.4018/IJMBL.291980

Megahed, N. and Hassan, A. 2022. A blended learning strategy: reimagining the post-Covid-19 architectural education. Archnet-IJAR: International Journal of Architectural Research, 16(1), pp. 184–202. Available at: https://doi.org/10.1108/ARCH-04-2021-0081

Nortvig, A.-M., Petersen, A.K., Helsinghof, H. and Brænder, B. 2020. Digital expansions of physical learning spaces in practice-based subjects - blended learning in Art and Craft & Design in teacher education. Computers & Education, 159, p.104020. Available at: https://doi.org/10.1016/j.compedu.2020.104020

Oxman, R. 2006. Theory and design in the first digital age. Design Studies, 27(3), pp. 229–265. Available at: https://doi.org/10.1016/j.destud.2005.11.002

Oxman, R. 2017. Thinking difference: Theories and models of parametric design thinking. Design Studies, 52, pp. 4–39. Available at: https://doi.org/10.1016/j.destud.2017.06.001

Özkar, M. 2011. Visual Schemas: Pragmatics of Design Learning in Foundations Studios. Nexus Network Journal, 13(1), pp. 113–130. Available at: https://doi.org/10.1007/s00004-011-0055-7

Schön, D.A. 1984. The architectural studio as an exemplar of education for reflection-in-action. Journal of Architectural Education, 38(1), pp. 2–9.

Schön, D.A. and Wiggins, G. 1992. Kinds of seeing and their functions in designing. Design Studies, 13(2), pp. 135–156. Available at: https://doi.org/10.1016/0142-694X(92)90268-F

Soliman, S., Taha, D. and El Sayad, Z. 2019. Architectural education in the digital age: Computer applications: Between academia and practice.

Alexandria Engineering Journal, 58(2), pp. 809–818. Available at: https://doi.org/10.1016/j.aej.2019.05.016

Ulger, K. 2018. The Effect of Problem-Based Learning on the Creative Thinking and Critical Thinking Disposition of Students in Visual Arts Education. Interdisciplinary Journal of Problem-Based Learning, 12(1). Available at: https://doi.org/10.7771/1541-5015.1649

Wood, D.F. 2003. ABC of learning and teaching in medicine: Problem based learning. BMJ, 326(7384), pp. 328–330. Available at: https://doi.org/10.1136/bmj.326.7384.328

Vrouwe, I., Dissaux, T., Jancart, S. and Stals, A. 2020. Concept Learning Through Parametric Design - A learning situation design for parametric design in architectural studio education. pp. 135–144. Available at: https://doi.org/10.52842/conf.ecaade.2020.2.135

SOUND MAP OF BIALYSTOK - OBJECTIVES AND FUNCTIONALITY

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ABSTRACT:

Digital audio maps, understood as a collection of auditory information implemented on geodatabases (e.g., Google Maps or Open Street Map), are virtual, multisensory representations of the built environment. Audio recordings collected on them, assigned to graphic markers (e.g., popular pins) usually refer to aspects of urban space that are interesting and important to map users. The markers collected within the boundaries of cartographic maps, in addition to audio recordings, are enriched with a variety of iconographic information (such as photos, descriptions or videos). The virtual micro-world of the sound map thus becomes a provider of multi-sensory experiences, resembling the sensations accompanying exploration of the real world. The sound layer of the map can thus become not only a carrier of information, but also of emotions, imaginations and memories, associated with specific places and events.

This article is an attempt to present a specific sound map, designed by the authors, relating to the phonic landscape of Bialystok. The purpose of the article is to present the Sound Map of Bialystok as an attractive and engaging tool for a digital tour of the city. The article presents the functionality and basic conceptual assumptions of the project, implemented with the participation of employees and students of WA and WI Bialystok University of Technology.

Keywords: sound studiues, soundmark, field recording, sound map, identity, digital representation

1. INTRODUCTION

Sounds accompany human existence starting from the prenatal period. Already in infancy, and therefore long before the ability to mentally take in the world, the newborn child betrays preferences and antipreferences to certain acoustic signals. Some of these reactions even have the character of reflexes (the so-called Moro reflex, i.e. the spreading of the arms and the tension of the body in response to a sudden, appropriately loud sound (Kosek 2023)). Gradually, the developing child learns to recognize and interpret sounds from his environment, as well as to give them the appropriate meaning derived from accepted cultural codes. The barking of a dog, the signal of an ambulance or the rumble of a thunderbolt are among the many sound signals through which a person recognizes the nature of an event and then assigns to it an adequate physical and emotional response. Interested in the sound of laughter, the chirping of birds, the sound of rain against the roof, or finally the melody of music, he acquires the ability to perceive the beauty of the surrounding world. In opposition to acoustic pleasure and harmony there are sounds perceived as “unpleasant to the ear”, disharmonious, noisy, unattractive - which man tries to tame by ignoring them, treating them as noise, relegating them to the role of perceptual background. Despite acquired defensive reactions, the human acoustic environment is often a source of considerable discomfort and even danger to the sensitive sense of hearing, connected to important internal organs (acting as a stressor on the nervous system, the heart).

The causes of so-called noise or sound pollution can be traced to the priorities of modern societies, striving for constant and unbridled growth through cutting-edge technology. The sounds of nature are increasingly being replaced by loud music in restaurants or the hum of traffic arteries, reflecting the rhythm of city life. As early as the 1970s, R. Murray Schafer, a Canadian composer and musicologist, warned of the disappearance of primordial soundscapes, giving way to noise coming from everywhere, understood as unwanted, annoying and unpleasant sounds (Bernat 2009, p. 101). The balance of the phonic environment, which guarantees the hygiene of living conditions, is disturbed by the mechanical sounds of civilization coming from everywhere. As M. Kapelanski notes, Western culture emphasizes visual perception, depriving the functioning of the other senses in the perception and exploration of the external world (Kapelański 2005, p. 108). Thus, one can venture to say that the senses, which are muffled by images and noise, are unable to fully process socio-cultural contexts, thus causing problems in finding a sense of identity and belonging for the individual.

This conviction prompted the authors of this article to reflect on the nature as well as the possibilities of scientifically investigating and recording the soundscape of Bialystok, a provincial city of about 300,000 people, located in northeastern Poland. The research focused on a web application created as part of an interdisciplinary project called “Sound Map of Bialystok” (SMB), implemented since 2021 by employees and students of the Faculty of Architecture and the Faculty of Computer Science at Bialystok University of Technology. Its result is a polysensory collection of information, presented in the form of a sound map presenting selected elements of the architectural space and soundscape of the city, including its key soundmarks. The purpose of this publication, describing the creation process, validity and functionality of the developed SMB, is to present the potential of low immersive ways of realizing the digital representation of the built environment. In this context, the authors described the areas of current usability of the Sound Map of Bialystok and outlined possible directions for further development.

2. THEORETICAL CONTEXT

The origins of sound studies are considered to be the activities, carried out by a group of Canadian scientists at Simon Fraser University led by R. M. Schafer, referred to broadly as "soundstudies." The Canadian composer and musicologist formulated the concept of "soundscape," calling it "our sonic environment [or] the ever-present array of noises with which we all live" (Schafer 1977), which was later expanded in his research by B. Truax to include the aspect of acoustic communication, pointing out the role of listening habits in the process of creating a relationship between the individual, society and the sonic environment (Truax 1984, p. 12). R. M. Schafer, considered the father of the acoustic ecology research trend and the founder of the so-called soundscape school, emphasized the importance of harmony and clarity of sounds in the context of activities aimed at eliminating acoustic pollution. As emphasized by R. Losiak, Schafer's approach to caring for the quality of the sonic environment is based on the idea of sound balance, that is, on a ratio favorable to human perceptual tolerance between harmful acoustic stimuli and valuable sounds that are threatened with extinction (Losiak 2017, p. 116-117). The mission to protect the original acoustic landscapes was continued by Schafer's collaborators, including P. Huse, H. Broomfield, B. Davis and H. Westerkamp, through the activities of a collective called the "World Soundscapes Project" (Kapelański 2005, p. 110) from 1972 to 1976 (Truax 1984, p. 75). The activists' field of interest included research on patterns of sound effects on people or cultural comparison of soundscapes. The project also involved documenting acoustic contexts and sound environments during so-called "field recordings" (Kapelański 2005, p. 110).

H. Westerkamp, a student and collaborator of R. M. Schafer, noticed the close connection between the auditory sphere and the visual sphere of geographic space. In the course of the sound walks (so-called soundwalks) she organized, she asked participants for their observations on the connections between the soundtrack heard and the visual aspect of the place traversed (Losiak 2017, p. 122). The archiving of fading soundscapes, carried out by WSP scientists, was the nucleus of audiovisual cartography, understood as a research methodology that deals with graphical visualization of features of the acoustic environment. As early as the 1990s, this approach was used by J. B. Krygier, an American geographer, to build a digital theoretical model based on sound variables such as location, loudness, pitch or duration of a sound signal (Hruby 2019, p.22). Guided, among other things, by the environmental perspective of R. M Schafer and the psychological outlook of B. Truax, he emphasized the localizability of sound as a key attribute of the representation of spatial relations (Krygier 1994, p. 150, 152). It can be assumed that the model created by Krygier represents one of the first manifestations of sound computer cartography, based on 2D digital maps (Hruby 2019, p. 22).

Due to the limitations associated with the implementation of non-visual messages (touch, smell or taste) through classical mapping methods, the graphical representation of geospatial data was the only tool to reflect the characteristics of physical reality. The change came with the advent of digital cartography, using map studies in the form of dynamic multimedia interfaces (Hruby 2019, p. 20). Distinguished by S. Thulin, sound-walking maps on a map base from well-known geolocation platforms like Google Maps or Open Street Map (so-called maps-of-sound--as-interfaces), not only enable spatial embedding of sound, but guide the user through a unique acoustic experience. Like the sound-walking maps developed within the WSP, they suggest valuable aural situations (so--called soundmarsks), highlighting key spatial qualities from the point of view of a given community (Thulin 2015, p. 8). Equipped with audial and visual attributes, they bring the user into an immersion, which F. Hurby presented as a "(...) the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant" (Slater and Wilbur 1997, in Hruby 2019, p.21). Internet sound maps thus transcend the framework of a static archive of sounds, actively creating links between viewers and the soundscape.

3. METHODS

The project called "Sound Map of Bialystok" has been implemented since 2021 by an interdisciplinary team, composed of employees and students from the Faculty of Architecture and the Faculty of Computer Science at Bialystok University of Technology. The goal guiding the originators was to create a digital representation of the phonic landscape of Bialystok in the form of a sound map, which is an archive of sounds shaping the identity of the city in different chronological periods.

The entire project was carried out in stages, as a sequence of structured steps. Step 1 involved the creation of a preliminary list of locations associated with the city's identity. Step 2 involved the collection of sound material, consisting of recordings of excerpts from contemporary soundscapes, as well as historically related excerpts from broadcasts. Step 3 was the editing work, which consisted of cleaning and cutting out interesting fragments of audio recordings. Parallel work progressed in Step 4, aiming to develop the sound map's user interface, its functionality and layout. The culmination of the process of creating the digital sound map of Bialystok was the development and implementation of graphic markers, along with the embedding of previously collected multimedia.

Implementation of the SMB Project

The research work began with the selection of a set of points (step 1) associated with sounds relevant to the city's identity. The criterion for selecting the initial set of markers, relating to contemporary and historical objects in the space of Bialystok (Table 3.1), was based on historical accounts, as described in specialized literature, and the subjective experience of the city, as conveyed in archival interviews and the local press.

Table 3.1. Example set of locations, source: own elaboration.

No.	Marker	District of Białystok
1.	Teatr Dramatyczny im. Aleksandra Węgierki	Centrum
2.	Basen na Stromej	Słoneczny Stok
3.	Kościół pw. Zmartwychwstania Pańskiego	Wysoki Stoczek
4.	Dworzec PKP	Przydworcowe
5.	Rynek na Bema	Bema
6.	Cerkiew pw. Świętego Jerzego	Nowe Miasto
7.	Białostockie Zakłady Graficzne	Białostoczek

The sounds, a key element of the service, were selected from the resources of Polish Radio Białystok and obtained during field recordings in various locations of the city (step 2). The audio files were edited in the free program Audacity, which consisted of cleaning sounds and cutting out interesting fragments (step 3). Each sound was described with attributes such as author, recording type and date, and source. The duration of each recording ranges from 5 seconds to about 3.5 minutes. The collected audio files were grouped by content type into "sounds", showing the situation of a selected part of the soundscape, and "report excerpts", from radio broadcasts. Complementing the virtual world of the sound map are photographs obtained from the archives of the Historical Museum Branch of the Podlaskie Museum, bearing the author's signature in the style of the website.

The development of a visual identity and the design of a website template, adapted to the expected way of navigation of future users, constituted the 4th step of the work on the site. The interface of the website was organized in the form of four tabs named "Map," "Leave a message," "About the project," and "Contact," containing in turn a map underlay with markers, an internal communicator, a description of the project and how to operate the website, and contact information for the website administrator. The implementation of the map primer was done through the Leaflet tool, which is a JavaScript library for creating interactive web maps. The map primer uses data from the Open Street Map website under the terms of the Open Data Commons Open Database license.

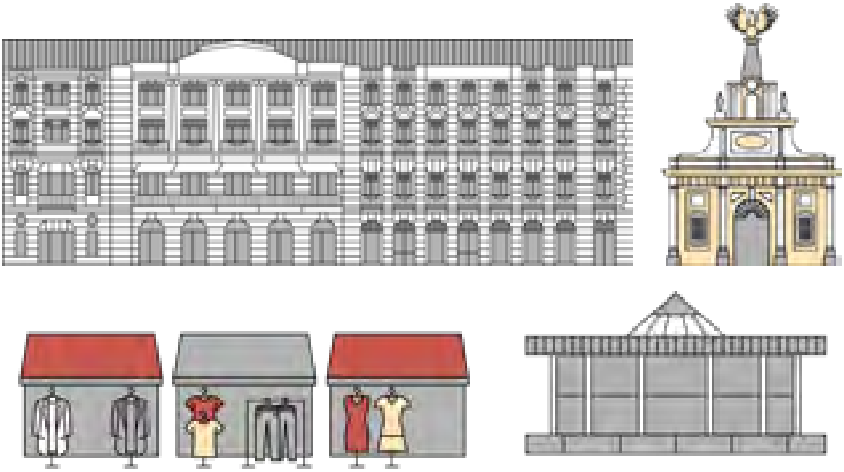

Fig. 3.1. Visual representation of selected locations, from left: Hotel Ritz, the Clock in the Great Gate of the Branicki Palace, the market on Kawaleryjska Street, Spodki, source: own elaboration.

The graphic layout of the test version of the website has been optimized for monitors with a 16:9 aspect ratio. A welcome screen, consisting of a few-second intro in the form of a pulsating #SoundMapBialystok inscription on a black background, replaces the main screen, divided into two main parts. The central area of the interface is occupied by a module with a map background, which in the “Leave a message”, “About the project” and “Contact us” tabs takes the form of a slider photo gallery. To its right a side panel was placed, designed to display variable content, depending on the user’s position in the service space. In the “Map” tab, selecting a tag triggers a change in the content of the panel from a general note about the project to an information fiche of the site. In the “Leave a message” tab, the right side of the main screen is occupied by the messenger section, which consists of a message entry box and a chat window. When you move to the other two tabs of the site, the text is displayed in the same place. In the next stages of the project’s development, it is planned to make the site fully responsive, so that the arrangement of graphic elements interacts with different monitor resolutions, including screens of mobile devices. The final stage of the work involved the graphic representation of selected sites (Fig. 3.1). The visualization of the objects' shapes and their embedding in the space of the cartographic map have been prepared to intuitively internalize the process of exploring the city's soundscape.

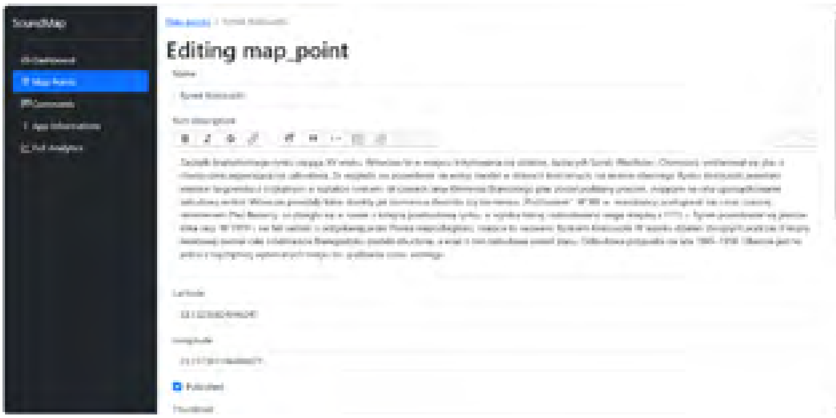

Fig. 3.2. View of the backend application panel used for adding points to the map, source: own elaboration.

The development of the sound map frontend proceeded in parallel with work on the backend application, responsible for managing data and operating the end-user accessible portion of the service. (Fig. 3.2). Like the website interface, the application was equipped with a number of functionalities, systematized into individual tabs. The area titled "Map points" runs the manual addition of location points (by specifying altitude and latitude) along with the embedding of recordings, photos, descriptions and graphics. The "App Informations" tab allows you to enter and modify the text visible in the frontend area of the "About the project" and "Contact" tabs. Moderation of content, posted via the internal messenger, takes place in the "Comments" panel, which contains detailed metadata for each comment, including user ID, message content and timestamp (date and time of creation), and a field for manual approval or rejection of submitted content. In addition, with the help of the "Full analytics" module, counting the number of hits on the site at the indicated time intervals, the site administrator has the ability to conduct simple statistics, showing the level of interest in the presented content.

4. RESULTS

The result of the work on the project so far is an interactive web application in beta version, available at: dzwiekowamapabialegostoku.pb.edu.pl. Spatial visualization of contemporary and past soundscapes of Bialystok has been realized based on a set of interactive geolocation points, most of which refer to a specific with some locations on the map being conventional. The amount of collected material influenced the expansion of the original list of sites to 90 locations. In order to increase the readability of the map, a grouping of points into polygons was introduced, displayed in the form of a perimeter and a number, indicating the number of objects in a given area. In the current version of the site, the transition from the view of polygons to detailed graphics is made using the mouse scroll or by clicking on the map area of interest (Fig. 4.1).

Fig. 4.1. Interface of the beta version of the Sound Map of Białystok website, source: own elaboration.

Selecting a marker from the map base space generates the opening of the object fiche in the side panel on the right side of the screen. The structured set of information for each point applies:

- graphic
s,
- object names,
- description,
- sounds,
- photos.

When the contents of the side panel exceed the size of the visible browser window, the user accesses the hidden part of the module using the scroll bar (Fig. 4.2). Audio material is launched by hovering the cursor over the selected recording name, while selecting one of the photos triggers a zoom in the width of the interface. The array of available activities closes with the possibility to get to the official website of the Bialystok University of Technology and the project's Facebook and Instagram profiles by selecting a hyperlink, hidden under the icons of the services in the top bar of the website template.

Fig. 4.2. View of the side panel after selecting the "Białystok University of Technology" marker, source: own elaboration.

The tab named "Leave a message" was designed with the intention of creating a field of mutual interaction between users of the service (Fig.4.3). The communicator, based on the mechanisms of social media applications, is equipped with a panel for entering messages, a window for selecting the country of origin, and a bar for independently setting the pseudonym under which the author of the comment appears. The chat box contains the messages published so far, thus becoming a place for the flow of thoughts, memories and experiences.

Fig. 4.3. View of the "Leave a Message" section, source: own elaboration.

The formula of the Sound Map of Bialystok allows exploration of the aural landscape at any place and time. The diverse audio material, consisting of ambient recordings, referring to the sounds of nature, vehicles, devices or people (e.g. the conversations of passers-by, the whirr of a motorcycle engine, the clatter of a printing machine, the splash of water, the quacking of ducks) and the audio anthology, expressed in stories and memories, influences the expansion of the visual message, expressed through graphics and photos, with another perceptual layer. The wide time horizon of the collected audio recordings, ranging between 1976 and 2022, allows the map's narrative to be enriched with a historical aspect, showing the transformation of the city's sounds over the decades. The digital environment of the application, combining layers of past and current soundscapes, creates a self-contained space-time where the past meets the present.

5. DISCUSSION

The process of creating a sound map of Bialystok, presented in this article, indicates the important role of audial signals in the context of oculocentric digital environments. As noted by B. Gibała-Kapecka "(...) visual impressions reach back to sensory experiences, resulting from auditory impressions" (Gibała-Kapecka 2020, p. 23). The representation of diverse areas of the urbanized environment (such as an urban bathing area, a downtown plaza, a shopping mall, an ice rink or a church), expressed in the form of markers and embedded multimedia, refers to both the external morphology of the selected location and its characteristic sound. V. Signorelli points to multisensoriality as an important feature of urban spaces, in which "(…) different sensory-scapes, characterized by blurred and fragmented boundaries changing over time (...)." (Signorelli 2015, p.2). The cited thought points to an important feature of twin digital environments, which, drawing on the richness of layers of meaning and the aesthetic and emotional qualities of sound signals (Geronazzo and Serafin 2023, p. 3), resemble the real prototypes.

The multifaceted nature of human existence emerges from the "spaces in between" carried by sound, understood as places of personal and collective experience, the relationship between the physical environment and ourselves (Anderson 2016), indicating the existence of individual and collective identity. A. Klopotowska notes the consistency between the unique repertoire of sounds of local societies and the trace of memories left by them. The author emphasizes that the activity of receiving and processing sound, commonly understood as a biological and intellectual ability of a person, has its origin in the psyche, spirituality, as well as codes of social Communications (Kłopotowska 2016). Flowing from the research of M. R. Schafer, the concern for preserving the unique sound compositions of modern cities (Schafer 1977), suppressed by the incoming noise from everywhere, is an attempt to stop the progressive loss of phonic identity of human living environments. The maps, enriched by the sonic element of identification and social awareness, go beyond the framework of audiovisual cartography, taking the form of mental maps. S. Bernat points out that "they are formed by experiences, images, memories, sounds and smells (...), in this regard, mental maps with their richness of impressions and experiences surpass traditional [cartographic] maps, referring to geographical experiences" (Bernat 2015, p. 82). The sensuality of sound maps, understood as archives of history, connects the personal perception of each user with experiences on a collective scale, contributing to the continuation of centuries-old traditions of a particular region.

Sound, as an intrinsic and sometimes intriguing element of the geographic and architectural environment, can be an important criterion influencing the choice of travel destination. The emergence of the phenomenon of sound tourism, which involves "traveling to places characterized by acoustic uniqueness or the presence of unique soundscapes," stems from the need to complement visual experiences with more complete and direct forms of learning about natural and cultural treasures (Bernat 2014, p. 25-26, 30-31). The sound map, as an innovative tool that allows the compilation of sound and image along with the location of this information in a specific place through geographic coordinates, complements and develops the traditional sightseeing process. The application's formula, built on sounds from the "here and now" juxtaposed with the sounds of the past, is an invitation to participate in a mental journey, allowing the listener to move through different dimensions of space-time. The expansion of the currently experienced sensory impressions into the dimension of emotional experience occurs gradually through the discovery of successive layers of meaning, stories or anecdotes. The sense of being part of a process, initiated by people who once lived in a given space, deepens the degree of familiarity with the existing urban fabric, creating a bond with a given place.

The forms of exploration of built space manifested by visually impaired people indicate the importance of non-visual perceptual impulses. As A. Klopotowska and M. Magdziak write "(...) in the case of blind and visually impaired people, architectural barriers, but also limited access to information about space, not only reduce the quality of life, but often constitute a serious functional limitation, preventing independent movement beyond the familiar zone." The authors highlight the importance of modern technologies in the context of creating alternative forms of representation of architectural space (Kłopotowska and Magdziak 2021). Consideration of sound maps in the above context indicates the high potential of the tool in the process of increasing the degree of accessibility of the built environment. The use of sound signals to convey relevant information about the natural, architectural, cultural and historical context of the mapped space allows compensation in the area of visual perception deficits. In the case of people with mobility impairments, the use of audio maps allows for advance preparation of sightseeing routes or exploration of the city from their own device.

Interactive applications of sound maps, built around cartographic primers from services such as Google Maps or Open Street Map, entail limitations in terms of modeling the digital world, resulting from the form of reality mapping adopted in GIS-type platforms. Well-known techniques of sound visualization, based on encoding meanings with graphic elements and colors (e.g., in noise emission maps), reduce auditory stimuli to a quantitative description of the environment, which leads to a significant loss of meaning and specificity of the acoustic phenomenon (Signorelli 2015, p. 5). The concept of an auditory map based on a set of geolocation markers and embedded multimedia, involves fragmentation of the real space, which distorts its virtual "twin". Attempting to build an immersive environment of a sound map, in which the listener takes dynamic actions that give meaning to digital locations such as walking, sitting or talking (Geronazzo and Serafin 2023, p. 6), becomes impossible due to the lack of connections between points on the map, which significantly reduces the level of immersion in the digital world. As F. Hruby, transforming 2D digital maps into immersive virtual environments (IVEs) would allow the user's experience to be extended along the lines of experiences in the physical world (Hruby 2019, p. 22).

The perception of sounds perceived by sensory-motor cognitive abilities, happens in a specific urban environment. Moreover, what is perceived by the human ear also depends on a number of variables, such as the time of day, the weather or the number of people. The flatness and rigidity of the structure of 2D maps, displayed on non-stereoscopic computer monitors, prevents to a large extent the externalization of sound, understood as a phenomenon opposite to the reception of auditory stimuli inside the head (Geronazzo and Serafin 2023, p. 16-17). Low immersive reality mapping techniques place the user in the position of a third-person spatial perspective, and therefore in the role of an observer rather than a participant in the micro-world of the sound map (Hruby 2019, p. 22, 23). It is worth noting the subjectivity of the process of creating the digital environment, which, in both its visual and auditory aspects, flows from the sensitivity and maturity of the authors. The end user of the application becomes acquainted, as it were, with the interpretation of the outside world, rather than its objective twin.

6. SUMMARY

The result of work under the "Sound Map of Bialystok" project is a beta version map application, based on a polysensory collection of information on selected elements of the city's architectural space and soundscape. The sound map formula, which assumes the exploration of the digital space of the website through the sense of sight and hearing, allows for the expansion of the visual content of traditional cartographic maps with a sound layer that activates the subjective experience of the user. The use of sound as the main element of the website:

- highlights the richness of the meaningful and emotional aspects of sound signals, making the SMB take the form of a mental map,
- shows the potential of sound signals to convey information about the natural, architectural, cultural and historical context,
- allows archiving the unique sound compositions of the city (noise protection),
- contributes to increasing the degree of accessibility of architectural space.

Intuitively traversing the sound map with geolocated points in the form of graphics, reflecting the features of architectural objects, city squares or events associated with the city, triggers in the user a set of social interpretation codes necessary to recognize and understand the character of a given location, which can deepen the impression of an almost physical presence in the environment. The virtual micro-world of the application highlights the most interesting aspects of the built space, which creates a number of opportunities related to the use of the sound map in such areas as:

- promotion of the city and region,
- development of tourism,
- archiving of cultural heritage
- formation of a sense of community and collective identity,
- increasing mobility of people with disabilities.

At the current stage of work, the participants of the Sound Map of Białystok project are expanding the database of collected audio recordings with contemporary sounds of the city in binaural and ambisonic formats, which will enhance immersion and the sensation of being "immersed" in sound. The audio recordings are being made using Neumann KU-100 and Sennheiser Ambeo VR microphones, as well as an 8-channel mobile sound recorder Zoom F8nPro (Antoniuk et al. 2025). The collected material will also be used to create new markers on the map, thus expanding the spatial scope of the sound map and improving its fidelity to the real-world counterpart.

Based on the research conducted, the authors identified potential areas for the development of the Sound Map of Białystok, aimed at increasing both immersion and accessibility. These include:

- supplementing the set of information describing selected locations with 360° video recordings,
- expanding the database of audio recordings with additional binaural and ambisonic sounds,
- increasing the number of existing markers,
- grouping points based on thematic categories and the criterion of "existing/non-existing object,"
- translating the website into English,
- optimizing the website interface for mobile screen resolutions,
- creating a dedicated mobile application.

According to the authors, further development of the Sound Map of Białystok project brings numerous social benefits, such as strengthening social identification and identity, as well as fostering and promoting civic engagement. Involving residents, designers, and city authorities in activities related to the dissemination and implementation of the SMB will enable the exchange of mutual experiences and expand the virtual world of the sound map with the unique perspective of each user.

BIBLIOGRAPHY

Anderson, I. (2016) *Soundmapping Beyond The Grid: alternative cartographies of sound*, [online], Journal of Sonic Studies, Vol. 11, https://www.researchcatalogue.net/view/234645/234646, [Accessed: 1 March.2025].

Antoniuk, P., Bagińska, K., Borys, K., Duniewicz, A., Mrozek, I., Wójcik, K. and Zieliński S. K. (2025) *The Sound Map of Białystok – From monophonic to immersive audio repository of urban soundscapes*, 158th Audio Engineering Society Convention, 22-24.05.2025, Warsaw, Poland.

Bernat, S. (2015) *Visualization of sound in the landscape on "sound" maps (Wizualizacja dźwięku w krajobrazie na mapach „dźwiękowych")*, Prace Komisji Krajobrazu Kulturowego, No. 28, p. 82.

Bernat, S. (2014) *Sound tourism as a new form of sustainable tourism*, Zeszyty Naukowe. Turystyka i Rekreacja, No. 1(13), p. 25, 26, 30, 31.

Bernat, S. (2009) *Sound quality management in public space (Zarządzanie jakością dźwiękową w przestrzeni publicznej)*, Space – Society - Economy Vol. 9, p. 101.

Geronazzo, M. and Serafin, S. (2023) *Sonic Interactions in Virtual Environments: The Egocentric Audio Perspective of the Digital Twin* [in:] Sonic Interactions in Virtual Environments, [online], Springer Cham, https://link.springer.com/book/10.1007/978-3-031-04021-4, [Accessed: 27 May.2025], p. 3, 6, 16, 17.

Gibała-Kapecka, B. (2020) *Spatial sound – the sense of surrounding through sound (Dźwięk przestrzenny – poczucie otoczenia dźwiękiem)*, inAW Journal, Vol. 1, No. 1, p. 23.

Hruby, F. (2019) *The Sound of Being There: Audiovisual Cartography with Immersive Virtual Environments*, KN - Journal of Cartography and Geographic Information, Vol. 69, p. 20-23.

Kapelański, M. (2005) *The birth and development of acoustic ecology under the banner of the soundscape school (Narodziny i rozwój ekologii akustycznej* *pod banderą szkoły pejzażu dźwiękowego)*, Muzyka, Vol. 50, No. 2, p. 108, 110.

Klopotowska, A. (2016) *Sounds of Architecture (Dźwięki Architektury),* Oficyna Wydawnicza Politechniki Białostockiej, Białystok.

Kłopotowska, A. and Magdziak, M. (2021) *Tactile Architectural Drawings—Practical Application and Potential of Architectural Typhlographics,* [online], Sustainability, Vol. 13(11), https://www.mdpi.com/2071-1050/13/11/6216, [Accessed: 29 May.2025].

Kosek, A. (2023) *Consequences of the persistence of unintegrated primitive reflexes among children in preschool and early school education* (*Konsekwencje utrzymywania się niezintegrowanych odruchów pierwotnych wśród dzieci w edukacji przedszkolnej i wczesnoszkolnej),* Pedagogika Przedszkolna i Wczesnoszkolna Vol. 11, No. 23, p. 49.

Krygier, J. B. (1994) *Sound and geographic visualisation*, Modern Cartography Series, Vol. 2, p. 150, 152.

Losiak, R. (2017) *Around the idea of acoustic ecology: concepts and practices (Wokół idei ekologii akustycznej. Koncepcje i praktyki)*, Studia Etnologiczne i Antropologiczne. Vol. 17, p. 116, 117, 122.

Schafer, R.M. (1977) *The Soundscape*, Destiny Books, Rochester Vermont.

Signorelli, V. (2015) *Soundwalking in virtual urban ambiances. Applying Game Engine Technologies in soundscape study,* Ambiances, Vol. 1, p. 2,5.

Thulin, S. (2015) *Sound Maps Matter: Expanding Cartophony*, [online], Lancaster University, https://eprints.lancs.ac.uk/id/eprint/83502/1/Sound_Maps_Matter_AAM.pdf [Accessed: 24 Jun.2025], p. 8.

Truax, B. (1984) *Acoustic Communication*, Ablex Publishing Corporation, Norwood, New Jersey, p. 12, 75.

Websites

The Sound Map of Białystok, source: dzwiekowamapabialegostoku.pb.edu.pl, accessed: 25.06.2025.

DIGITAL TRANSFORMATION IN ARCHITECTURE: CHALLENGES IN THE CONTEXT OF EGYPT

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ABSTRACT:

In the era of dynamic urbanization in Egypt and a growing demand for housing, the implementation of digital tools in architectural design processes poses significant challenges. This paper critically examines the potential and limitations of advanced technologies, such as Building Information Modeling (BIM) and parametric design, within the rapidly evolving infrastructure context of Egypt. These digital solutions facilitate more precise management of project data, reduce investment costs, and streamline construction procedures, thereby promoting urban development. Moreover, modern technologies may serve as an impetus for improving project quality and fostering sustainable urban planning practices.

However, the high costs of implementation, substantial licensing fees, and the need for specialized technical infrastructure and training constitute significant barriers to widespread adoption. As a result, these technologies are primarily employed by large international firms, equipped with considerable financial and technical resources, while local architects remain reliant on conventional software, such as AutoCAD. This situation risks marginalizing local practices and perpetuating market imbalances in developing countries. The aim of this study is to delineate the interdisciplinary challenges and opportunities associated with the adoption of digital tools in Egypt's architectural sector. The proposed hypothesis suggests that although the introduction of BIM and parametric design can enhance project efficiency, their limited accessibility among local practitioners reinforces existing market disparities, thus adversely affecting the balance of power in the industry and questioning the impact of digitalization on the evolution of architecture in developing nations.

Comparative studies indicate that insufficient institutional support and limited financial resources are key obstacles. These findings underscore the need to develop comprehensive training programs and enhance technological support, which are essential for facilitating digital transformation in architecture. Ultimately, the integration of digital tools may help equalize opportunities between large international and local firms, fostering a more balanced and sustainable architectural landscape in developing regions worldwide.

Keywords: Computational Design, Inclusive Digital Transformation, Technological Inequality, Postcolonial Spatial Practice, Global South Urbanism, Architecture in Egypt

1. INTRODUCTION

In recent decades, digital tools have significantly influenced architectural design, construction project management, and the implementation of complex urban development projects. Technologies such as building information modeling (BIM), parametric design, and open source platforms are increasingly recognized as essential for ensuring precision, coordination, and efficiency in design processes. However, the digital transformation of architecture is not progressing evenly across the globe. Infrastructure, economic, and institutional constraints mean that the pace and scale of digital implementation vary significantly, both between and within countries.

Egypt represents a particularly interesting case in this context. On the one hand, the country is pursuing prestigious large-scale urban developments - such as the New Administrative Capital or New Al-Alamein City - often involving international studios with advanced technological and digital facilities. As UN-Habitat notes, rapid urbanisation in developing countries is associated with a unique tension between growth and inclusivity, making spatial transformations particularly vulnerable to technological inequalities (UN-Habitat, 2020). On the other hand, a large part of local architectural practices, mostly outside the main agglomerations, still operate on the basis of traditional design methods and limited resources. The aim of this article is not to generalize the situation of the entire Egyptian architectural sector, but to capture the internal complexity and unevenness of the digitization process in the context of dynamic but heterogeneous urban transformations.

Importantly, the issues discussed in this text are not unique to Egypt, African countries, or the Middle East. The phenomenon of digital exclusion—or rather, limited access to digital tools—also affects many architectural studios in Europe, including Poland. Even where digital infrastructure is well developed, smaller offices often refrain from implementing BIM or parametric design due to licensing costs, the lack of profitability of investments in training, and the need to upgrade computer equipment. Thus, the problem of adapting digital technologies concerns not only the geography of the global South, but also structural inequalities within the sector itself.

This article attempts a critical analysis of the digitization of architecture in Egypt, a country that is currently one of the largest construction sites in the Middle East and North Africa region. Particular attention is paid to the tension between the potential of modern digital tools, such as BIM and parametric design, and the actual availability of these technologies to local design entities. The text raises questions about whether digitization can serve to promote better design practices or whether, under current conditions, it perpetuates global and local inequalities. As Halpern and Mitchell (2017) note, "smart technologies and data systems are not neutral tools but instruments that extend older logics of colonialism, control, and capital accumulation into new spatial and political territories".

The article also aims to reflect on the role of architects and scientists in this process. How can the architectural community support more democratic access to technology? Can scientific research contribute to reducing barriers, or does it rather legitimize the status quo? These questions become particularly relevant in countries with dynamic urban development, such as Egypt, where design decisions are increasingly made outside the boundaries of the local system of values, competencies, and needs.

2. METHODOLOGY

This paper takes a qualitative approach, focusing on content analysis of the foundational sources and comparative interpretation of publicly available materials. The aim was to capture contemporary trajectories of digitalisation in Egyptian architecture, with a particular focus on technologies such as BIM (Building Information Modelling) and parametric design.

In the first stage, documentary and industry materials were analysed, including reports from international institutions (e.g. UN-Habitat, World Bank), technology publications (e.g. Autodesk, Graphisoft) and academic papers. The collected sources were analysed to identify key themes: the indicated benefits and barriers to the implementation of digital technologies and their impact on shaping architectural practice in developing countries.

Complementing the analytical material was a study of selected architectural firms operating in the Egyptian market. Ten firms with diverse profiles were included in the study, and were purposively selected based on their online activity, visibility in industry sources and availability of digital data. The way they communicate their use of digital tools, the extent of their declared technological specialisation and references to industry standards were analysed. Although this method does not allow for full representativeness, it provides qualitative insights into the practices of selected actors operating in a diverse economic environment.

The material collected was interpreted using a SWOT framework and a proposed four-factor model (computing, cost, organisation, context) that structures the main determinants of digital tool implementation in the Global South. This framing allows to deepen the understanding of digital transformation in architecture and to formulate recommendations for practice and academia.

3. LOCAL PRACTICE AND DIGITAL TOOLS: A STUDY OF SELECTED OFFICES

In order to better understand the realities of digital technology implementation in Egyptian architecture, a qualitative analysis of the content made available to the public by selected design offices was carried out. Ten entities, diverse in terms of scale of operations, organisational profile and geographical coverage, were included in the analysis. A key criterion for selection was their visibility in the international or national space, their visibility in the professional media and the availability of substantive information on their official websites. The analysis is exploratory in nature and makes no claim to statistical representativeness.

The aim of the analysis was to identify to what extent architectural firms in Egypt claim to use tools such as Building Information Modelling (BIM) or parametric design, and what place such solutions occupy in their communication and competency strategy. Particular attention was also paid to the organizational nature of the offices analysed - i.e., whether they operate exclusively in the local market or participate in international projects as partners or contractors.

Table 1: Study of selected architectural offices in Egypt

Name of a company	Location	Declaration of using BIM	Declaration of using parametric design	Range	Profile of a company
ECG (Engineering Consultant Group)	Cairo	Yes	No data	Africa, Asia, Europe	International engineering consultancy
Dar Al-Handasah	Cairo	Yes	No data	Africa, Asia, Europe, North America	Global design and consulting firm
ACE Moharram Bakhoum	Cairo	Yes	No data	Africa, Asia	International engineering consultancy
Shahira Fahmy Architects	Cairo	Yes	No data	Africa, Europe, North America	Authorial design studio with international exposure

Living In Interiors	New Cairo	No data	No data	Africa, Asia	Regional practice, interior design
Architecture Algorithm	Cairo	Yes	Yes	Africa, Asia	Locally based practice with international orientation
HM Studios	Cairo	No data	Yes	Africa, Asia	Regional architecture studio
Style Design	Maadi, Cairo	No data	No data	Egypt	Regional interior design studio
Dar Arafa Architecture	New Cairo	No data	No data	Egypt	Local architectural consultancy
Dewan Architects & Engineers	Egipt	Yes	No data	Africa, Asia	Local architectural consultancy

The conducted analysis indicates a correlation between the use of digital tools and a firm's position within the architectural market structure—both geographically and organisationally. Technologies such as Building Information Modelling (BIM) are predominantly found in international or engineering-oriented firms that are firmly embedded in global construction and infrastructure networks. In this context, digitalisation does not appear as a universal instrument of modernisation but rather as a filter that privileges entities with substantial capital, complex organisational structures, and access to transnational professional networks.

This phenomenon is widely observed in the literature. As Ayinla and Adamu (2018) note, small and medium-sized enterprises (SMEs) in the architecture, engineering and construction (AEC) industry are often regarded as part of the 'Late Majority' or even 'Laggards' in BIM adoption, whereas larger organisations act as 'Innovators'. Similarly, Dainty et al. (2017) warn that political reform agendas centred on BIM—although seemingly neutral—may in practice disenfranchise small firms unable to meet technological or investment requirements.

Among Egyptian firms operating primarily in the national market, the adoption and communication of digital technologies is notably less common. This can be attributed to a range of factors, including the high cost of licences, a lack of training resources, and limited technical infrastructure. It also reflects a different mode of practice—one that relies more on local networks, hand-drawn processes, and a reduced participation in technically complex, large-scale projects. It is important to note, however, that the absence of explicit references to digital tools does not necessarily indicate their absence in practice; rather, it may reflect different communication strategies or a lower emphasis on technological self-presentation.

As recent studies have shown (Rethinking the Digital Divide of BIM Adoption, 2024), the digital transformation of the AEC sector is far from uniform. Structural inequalities in access to digital tools persist and often deepen. While these technologies are technically accessible, their implementation remains heavily contingent upon economic, organisational and institutional factors. This raises the question of whether the current trajectory of architectural digitalisation in Egypt—and more broadly, in the Global South—is reinforcing existing inequalities, with advanced technologies functioning not as instruments of inclusion, but as mechanisms of professional and systemic selection.

4. BARRIERS TO THE IMPLEMENTATION OF DIGITAL TOOLS IN EGYPTIAN ARCHITECTURE

Although the advantages of using digital tools in architecture - such as building information modelling (BIM) and parametric design - are widely reported in the literature and industry documents, their implementation in the Egyptian context faces a number of significant barriers. These are multidimensional, encompassing economic, institutional, organisational and infrastructural constraints. As Underwood and Ayoade (2016) note, successful digitisation in architecture depends not only on the availability of technology, but also on the structural conditions for implementation, including the level of education, public policies and market practices.

4.1 Economic barriers

Despite increasing pressure to implement innovation, the architecture and construction sector is still characterised by low productivity and resistance to digitalisation - not least because of its cost and complexity (McKinsey Global Institute, 2017). Commercial software, such as Autodesk Revit or Graphisoft ArchiCAD, requires constant licence fees and investment in an appropriate hardware infrastructure. Moreover, making full use of their functionality requires specialised staff and paying for professional training. For many smaller architectural offices in Egypt, especially outside the main urban centres, this type of expenditure is difficult to justify economically and often exceeds the real operational capacity.

This phenomenon is part of a broader regional context - as Dari et al. (2023) note, in the Middle East and North Africa, financial constraints and shortages of technical and human resources are among the most significant barriers to the implementation of BIM technology, leading to a selective and uneven pace of digital transformation.

4.2 Institutional and organisational constraints

Digitisation of the design process requires not only financial investment, but also a systemic educational and organisational background. Although some Egyptian technical universities are attempting to introduce BIM-related content, the presence of this issue in their curricula is fragmented. As Nagy and El-Karim (2022) point out, only 14% of BIM users in the MENA region have acquired these skills as part of their studies, while the majority train on their own, outside academic institutions. Also, a study by Khalifa, Attia and Awad (2024) shows that education programmes in Egypt are still mainly focused on teaching traditional CAD tools, and the introduction of BIM is usually limited to single classes, without deeper embedding in coordination processes and teamwork. Similar findings are brought by analyses from Menoufia University, where Saleh and Abdalla (2024) indicate that the integration of BIM in the curriculum is modular and technical, which hinders the building of full digital competencies at the professional level.

Outside the academic sphere, the lack of uniform implementation standards and legal regulations to support the implementation of digital technologies also remains a problem. Implementations of BIM and related tools most often depend on the goodwill of investors or individual decisions of design office management. As Succar and Kassem (2015) note, "without policy frameworks and regulatory incentives, the diffusion of digital workflows tends to remain selective, opportunistic, and fragmented".

4.3 Conclusions and implications

The observations collected indicate that the digitisation of architecture in Egypt is taking place in an inconsistent and selective manner. The greatest benefits from the use of BIM and other tools are being achieved by studios operating in international projects with adequate budgets and staff resources. Small, local studios, despite their often high design competence, are unable to cope with the hardware, financial and organisational demands of fully implementing digital working methods.

Open-source alternatives, although promising in terms of economic accessibility, entail self-learning, adaptation and implementation risks. Without support from public institutions or the industry community, these tools remain difficult to use effectively in a commercial context. As Kitchin (2014) notes, technologies are not inherently inclusive - "their impact is always mediated through political, economic, and institutional structures".

As a result, the process of digitisation – rather than fostering the democratisation of design practices – may in fact deepen existing structural inequalities, both locally and globally. The literature highlights that digital innovation, although formally inclusive, often serves to strengthen the position of technologically privileged actors, thereby marginalising smaller and less resourced practices (Dainty et al., 2019).

5. THE 4C MODEL: STRUCTURAL CONDITIONS FOR THE IMPLEMENTATION OF DIGITAL TOOLS

To systematise the interdependent factors influencing the digitalisation of architecture in Egypt, a 4C framework has been developed. This model organises the observed challenges and potentials into four complementary dimensions: computing, cost, capacity, and context.

5.1 C1 – Computing: Tools and Technology

Digital technologies, particularly Building Information Modelling (BIM), offer substantial improvements in project coordination, documentation accuracy, and information management throughout a building's lifecycle. However, their effective use depends on access to advanced software, familiarity with interoperability standards (such as IFC), and sufficient hardware infrastructure. These conditions often exceed the capacity of small, locally based firms. Open-source alternatives—such as FreeCAD with BlenderBIM—can help bridge this gap, but they lack institutional support, widespread adoption, and industry maturity.

5.2 C2 – Cost: Financial Burden and Investment Risk

The most frequently cited barrier remains the high cost of software licences, hardware upgrades, and hiring qualified personnel. For many small and medium-sized offices, especially those operating in low-margin segments of the market, investment in digital technologies is perceived as economically unjustifiable. Additionally, there are few mechanisms of public support (e.g. grants, tax incentives) that could encourage or de-risk the adoption of digital practices within the architectural sector.

5.3 C3 – Capacity: Organisational Structures and Workflows

Large international firms often maintain in-house BIM departments and operate according to their own quality assurance protocols and modelling standards. These capacities enable them to scale projects, compete globally, and implement digital tools efficiently. By contrast, many local firms in Egypt continue to function under a traditional, author-based model, where project work is done manually and organisational flexibility substitutes for digital coordination. The absence of internal standardisation poses difficulties for introducing tools that require interdisciplinary teamwork, such as those used for collaborative BIM workflows.

5.4 C4 – Context: Regulation, Market, and Institutional Environment

Unlike countries where BIM has been made mandatory in public procurement processes—such as the United Kingdom, Germany, or Scandinavian nations—Egypt does not yet have a regulatory framework that actively promotes digitalisation. Legal and procedural standards for digital modelling, data interoperability, or project archiving are either underdeveloped or absent altogether. Furthermore, educational and training infrastructure for digital tools remains uneven, particularly outside of major cities. Global investment patterns—particularly those from Europe and the Gulf region in Egypt's coastal developments—have increased the presence of foreign firms, but this process often excludes local actors from technological and decision-making processes.

5.5 Conclusion: Reflections on the 4C Model

The 4C model demonstrates that digitalisation in architecture depends not solely on access to technology, but on a wider constellation of structural, educational, and economic conditions. An integrated approach is required—one that addresses hardware access, cost mitigation, skill development, and regulatory clarity. Crucially, the goal should not be to accelerate digitalisation at all costs, but to ensure that it becomes an inclusive and equitable process that benefits a wide spectrum of practitioners. If managed uncritically, digital tools may reinforce professional and geopolitical asymmetries; but if implemented with awareness of structural inequalities, they can help reduce them.

6. SWOT Analysis: Digital Transformation in Egyptian Architecture

In order to synthesise the key challenges, opportunities, and structural conditions influencing the implementation of digital tools in Egyptian architectural practice, a SWOT framework (Strengths, Weaknesses, Opportunities, Threats) was employed. This analytical model enables a balanced assessment of the potential and limitations of digitalisation, taking into account the diverse and uneven character of design practices in Egypt.

Table 2: SWOT analysis of digital transformation in architecture

Strengths	Weaknesses
Potential to increase design and coordination efficiency Possibility of reducing construction errors and project costs Growing number of international projects requiring BIM Presence of firms with experience in implementing advanced digital tools	High cost of software licences and professional training Insufficient technical infrastructure in many regions Absence of national standards or regulatory support for digitalisation Skills gap and limited access to training for smaller local firms
Opportunities	**Threats**
Growth of digital education and open-source learning models (e.g. online courses, e-learning) Potential for international support via partnerships and research-education programmes Integration with the global design services market through BIM proficiency	Further dominance of global firms and marginalisation of local actors Risk of digitalisation reinforcing dependency dynamics and global asymmetries Digital tools perceived as a costly luxury rather than an inclusive enabler

The SWOT analysis confirms that digitalisation in Egyptian architecture has strong transformative potential but remains constrained by deep structural barriers. On the positive side, digital tools offer tangible benefits for project quality, coordination, and investment management—especially for firms engaged in international markets, where BIM has become a formal requirement.

However, weaknesses highlight significant limitations in access and affordability, especially among local practices that lack the financial, technical, or organisational resources needed for digital transition. In many cases, these firms also operate in environments where market incentives and client expectations do not strongly favour technological adoption.

Opportunities lie in the growing availability of open-source platforms and educational content, which can support broader accessibility—provided there is institutional and infrastructural backing. These resources could help bridge the digital divide, particularly through locally adapted training models.

Threats, meanwhile, point to a growing imbalance between global and local actors. International firms often lead high-profile development projects, bringing capital and technology but without necessarily involving local professionals in meaningful or sustained ways.

As a result, there is a risk that digitalisation, rather than fostering inclusion and equal participation, may reinforce existing inequalities within both national and global design ecosystems.

7. CONCLUSIONS AND FINAL REFLECTION: DIGITALIZATION AS A TOOL FOR INCLUSION OR INEQUALITY?

This article attempts to take a critical look at the conditions for implementing digital tools in architecture in the context of Egypt—a country undergoing rapid urbanization, where investment, social, and environmental pressures require modern design solutions. The analysis shows that although technologies such as BIM and parametric design offer a number of advantages in terms of efficiency, coordination, and project quality, their implementation is limited to a narrow group of entities—most often large foreign offices or local companies linked to the global market. Access to advanced tools in Egypt remains highly selective and is determined by economic, organizational, and institutional factors. In practice, this means that digitization does not currently serve as a tool for democratizing the architectural sector, but rather reinforces existing divisions between local and international architects. Similar phenomena can also be observed in Central and Eastern Europe, where small architectural studios often do not implement digital solutions for similar reasons — limited financial resources, lack of access to training, and low levels of institutional support. In this context, it seems particularly important to reflect on the role of science and architecture as socially responsible disciplines. The digitization of architecture cannot be understood solely as technological progress—it is also a political and ethical choice that determines who has access to knowledge, tools, and participation in shaping space. As researchers operating in the European context, we should be aware that the knowledge and technologies at our disposal can become both a factor in equalizing opportunities and a tool of contemporary domination—including architectural neocolonialism. Therefore, science should act as a catalyst for inclusive change, rather than a reproducer of existing power structures. This requires active engagement in the process of popularizing knowledge and technology—through the creation of open educational materials, international cooperation, support for local initiatives, and research that takes into account the perspectives of marginalized actors. As Latour (2004) notes, 'Every time we scientists speak, we reshape the world we describe.' The responsibility of scientists does not end with analysis — it begins where knowledge has a chance to reach those who have been excluded from it until now.

REFERENCES

Dainty, A., Leiringer, R. and Harty, C. (2019) "BIM and the small construction firm: a critical perspective", *Construction Management and Economics*, Vol. 37, No. 1.

Dari, A., Al-Yousef, K. and Al-Assaf, H. (2023) "BIM adoption in the construction industry of the Middle East and North Africa (MENA): barriers and opportunities", *International Journal of BIM and Digital Construction*, Vol. 8.

Eastman, C. et al (2011) *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors,* John Wiley & Sons, Hoboken, NJ.

Khalifa, M., Attia, S. and Awad, N. (2024) "Integrating BIM education in Egyptian architectural curricula: current practices and future prospects", *Egyptian Journal of Engineering Education*, Vol. 12, No. 1.

Kitchin, R. (2014) *The Data Revolution: Big Data, Open Data, Data Infrastructures & Their Consequences*, Sage, London.

Latour, B. (2004) *Politics of Nature: How to Bring the Sciences into Democracy,* Harvard University Press, Cambridge, MA.

McKinsey Global Institute. (2017) *Reinventing Construction: A Route to Higher Productivity,* McKinsey & Company, New York.

Nagy, K. and El-Karim, A. (2022) "Educational pathways for BIM in MENA nations: an empirical study", *Journal of Architectural Education in the Middle East and North Africa,* Vol. 5, No. 3.

Saleh, M. and Abdalla, F. (2024) "BIM pedagogical interventions at Menoufia University: assessment and recommendations", *Menoufia University Journal of Engineering,* Vol. 7, No. 2.

Succar, B. and Kassem, M. (2015) "Macro-BIM adoption: conceptual structures", *International Journal of Building Pathology and Adaptation*, Vol. 33, No.3.

Underwood, R. and Ayoade, O. (2016) "Strategic challenges in digital construction adoption: a global perspective", *Journal of Construction Engineering and Management*, Vol. 142, No. 8.

UN-Habitat. (2020) "World Cities Report 2020: The Value of Sustainable Urbanization", *United Nations Human Settlements Programme*, Nairobi.

MONITORING SYSTEM OF INTERIOR ENVIRONMENTAL PARAMETERS AND ENERGY MANAGEMENT, AS A KEY ELEMENT OF BUILDING AUTOMATION.

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ABSTRACT:

Monitoring system of interior environmental parameters and energy management in the laboratory building of the Faculty of Architecture at BUT, as a key element of building automation.

Centralized building automation is now one of the most important tools for optimizing building energy management, enabling 9 to 26% savings in the heating system as a result of automation. Building automation systems require the creation of a thoughtful system of sensors that monitor the performance of a building's infrastructure at multiple levels - demand, performance effects and energy consumption. An analysis of the BMS system and installations in the laboratory building of the Faculty of Architecture at the Bialystok University of Technology was carried out

in terms of the possibility of upgrade to optimize energy management. The existing systems for shaping the indoor environment, energy management, monitoring physical parameters and energy consumption and controlling devices were presented. The automation and controll system was classified and evaluated in accordance with the current EN standard.

Keywords: BACS, BMS, energy efficiency, building automation

1. INTRODUCTION

In the era of global climate change, the European Union policy, represented in the directives, EPBD - Energy Performance of Buildings Directive, EED - Energy Efficiency Directive, and RED - Renewable Energy Directive, considers increasing the energy efficiency of existing buildings to be one of the leading challenges in the field of construction industry.3 The modernization of a building aimed at improving energy efficiency should be preceded by an economic and ecological optimization procedure, which allows for determining the most cost-effective scope of investment and will contribute to the greatest reduction in greenhouse gas emissions in relation to investment costs. A key obstacle in Poland is the lack of qualified workers in the construction and design industry who are able to meet the needs of the market resulting from EU policy objectives12. This highlights the need for rational management of resources in order to meet the requirements of energy efficiency of buildings.

Improvement of the energy efficiency of buildings is possible through comprehensive modernization or specific building elements:

- modernization of the thermal envelope consisting in increasing the thermal insulation of building partitions;
- modernization of the heat source leading to a reduction in the demand for primary energy contained in the fuel;

- installation of local renewable energy systems (mainly PV);
- installation of mechanical ventilation with a recuperation system;
- equipping the building with an automatic energy control and management system;

The modernization of building automation and control (BAC) systems involves both the modernization of installations in buildings and allows for an increase in the share of renewable energy sources in the energy balance, such as direct solar radiation, storage of energy produced by local PV systems, and interaction with smart energy distribution networks through energy storage in buildings.

The conducted case study study of typical multi-family buildings in Poland (thermomodernized in the years 1990-2015) determined the possibility of reducing the demand for primary energy (EP) by modernizing individual elements in the building 11- in the field of heating and domestic hot water (DHW) preparation:

- modernization of the the thermal envelope to the 'nearly zero energy consumption' building standard - by 29-32%
- replacement of fossil fuel-based heat sources (network or a natural gas boiler) with heat pump-based systems – 34-37%
- installation of PV installations on the roofs of buildings (multi-family buildings with flat roofs) – 5-15%
- installation of mechanical ventilation systems – 8-10%

Case study research on improving the energy efficiency of a building by modernizing the building automation and control system (BACS), using the method described in the standard PN-EN ISO 52120-1:2022 ,8 determined the possibility of savings of up to 26%. 6Theoretical studies covering all systems in the building, including cooling and lighting, indicated the possibility of achieving savings of up to 71% as a result of BACS modernization.[9]

The modernization of building control and automation systems involves the installation of control equipment with control algorithms tailored to specific needs, and therefore usually does not require construction work, making it often the fastest method of improving energy efficiency in a building, with the least interference in its structure and the least disruption to its ongoing use. Only the aforementioned problems with the availability of highly qualified employees may mean that this will not be the cheapest method, ensuring high energy savings.

BAC makes it possible to control all installations in the building, the operation of which is associated with energy consumption, in order to maintain the required comfort conditions in the interiors. Complex and integrated energy-saving systems can take into account data on the current use of the building and the actual comfort needs in operation, thus avoiding unnecessary energy consumption and consequently CO2 emissions.[7]

The energy efficiency of systems can be improved through automation of processes and control in three areas:

– Demand side – controlling energy emissions in the building based on actual usage comfort demands
– Energy supply side e.g. turning on peak sources as needed
– Distribution side – e.g. runnig pump motors or energy storage load prediction algorithms

A key element of BACS that ensures the ability to control current comfort needs is a system for monitoring indoor environmental parameters, outdoor conditions, system operating status, and energy flow. Recording this data, in turn, enables the use of machine learning and deep learning methods to increase system efficiency through better use of energy storage.[5]

2. METHOD

This article describes the automatic control and control system in the LEEARE building and systematizes BACS using the methods and procedures described in the PN-EN ISO 52120-1 standard in order to identify opportunities to improve the system. Since the simplified method described in the standard is applicable to the designed state, a partial analysis was carried out using it, consisting in an attempt to determine the efficiency class of the existing BACS in the building and the possibility of increasing it. The standard belongs to a family of standards compliant with the EPB (Energy Performance Building) standard, which aims to harmonize the methods for determining the energy characteristics of buildings and to support EU directives, including the EPBD (Energy Performance Building Directive). The standard defines the possible methods of controlling installations in a building, assigns them efficiency classes and presents methods for calculating energy efficiency for planned BACS modernizations.

The standard defines the energy efficiency classes of building automation and control (BAC): 1

- Class D – the automation system has no impact on the energy efficiency of the building;
- Class C – automation systems have a minimal impact on the energy efficiency of the building thanks to the central control of technical installations and individual control of energy consumption in individual rooms – in the standard, the class refers to the standard BAC;
- Class B – High impact on energy efficiency thanks to distributed control of each energy receiver in the building and communication of the receivers with central systems and taking into account

the needs of user comfort at the basic level – in the standard refers to advanced BAC taking into account schedules;
- Class A – Very high impact of BAC on the energy efficiency of the building thanks to a distributed control system equipped with a system of automatic identification of energy demand in each room and control of the efficiency of energy sources in the building, depending on the total demand – in the standard refers to high-energy efficiency systems.

The standard presents a method for the initial assessment of the possibility of improving the efficiency of BACS for a designed or existing building intended for renovation, consisting in the determination by the designer or investor of the preferred automation solution using tables with assigned automation efficiency classes. The method can also be used by inspectors to assess whether the solution used meets the design intent. The standard specifies a method for calculating the impact of the automation solutions taken into account on the energy efficiency of the building. When determining BAC efficiency classes, only those solutions that have a significant impact on energy consumption were taken into account.

The following control levels are defined: 4

- (0) - no control at all;
- (1) - central automatic control;
- (2) - individual automatic control of receivers in each room;
- (3) - individual automatic control of receivers in each room with communication with the central system;
- (4) - individual automatic control of receivers in each room with communication with the central system and identification of energy demand;

EN ISO 52120-1 presents methods for calculating potential savings resulting from Upgrading of a Building Automation and Control System (BACS) : detailed calculation method based on energy simulation; Factor method - for initial estimation of energy savings based on factors and previously metered or calculated energy demand. The use of the indicator method consists in assessing the possibility of improving the energy efficiency of the building by determining the system class for the existing and target or designed state. In the next step, the savings indicator is calculated on the basis of the standard data by which the measured or calculated energy demand for the system is multiplied. The methods indicated in the standard can be used both for existing buildings intended for modernization and for designed buildings. However, the final investment decision should be preceded by economic optimization calculations, taking into account investment and operating costs.2

The energy saving index was calculated using a simplified method according to formula 1. The calculations were carried out for all relevant systems in the building, using indicators specified in the standard.

Formula 1 – Method for calculating the efficiency of BAC solutions, on the example of a heating system (EN ISO 52120-1:2022)

$$Q_{H,tot,BAC} = (Q_{H,tot})\ \frac{f_{BAC,H}}{f_{BAC,H,ref}}$$

Where:

QH,tot,BAC – total energy for heating taking into account BAC e-efficiency classes

QH,tot – energy demand for heating – calculated, together with energy losses in the system

fBAC, H – BAC efficiency ratio (specified for the designed efficiency class)

fBAC, H, ref – BAC benchmark (existing or standard)

The energy saving index was calculated as a ratio of the indicator for the designed state to the existing state. The design condition was determined only by the selection of a solution that does not require a significant investment in the expansion of the installation, but only by the use of existing installations and the implementation of control algorithms.

Photo 1. LEEARE building – Laboratory of Energy Efficiency Architecture and Renevable Energies. Photo: M. Tur 2025.

The LEEARE building has a centrally controlled BMS (buiding management system) and is equipped with an extensive measurement system, the elements of which are both integrated with individual installations and constitute a separate monitoring system. All monitoring elements have a physical connection to the BMS.10 The system in the building consists of 473 devices with 653 points that can be recorded for data recording. Table 1, in Annex A, presents all devices providing BMS data on the condition of the building, the purpose of the data, the main protocol of communication between the device and the central control unit of the BMS, units of recorded data, recording parameters, location and identified problems.

Photo 2,2. Double glass facade with TABS hot air distribution equipment visible; heating and cooling circuits with automation equipment – actuators, adjustable circulation pumps and heat meters. Photo: M. Tur 2025.

An assessment of existing automation solutions was carried out, along with the identification of possible solutions that could be implemented without the need for installation expansion, but only by using existing components that were not currently used for automation purposes. This is an attempt at the practical application of a holistic approach, its first step being the functional linking of various installations and the process of shaping the parameters of the internal environment through them. It is also crucial to take into account the variability of how the building is used by its occupants and the variability of external environmental conditions, which are responsible for the supply of renewable energy (solar energy, wind) and resources in the form of rainwater. An attempt was made to determine the automation efficiency indicators for

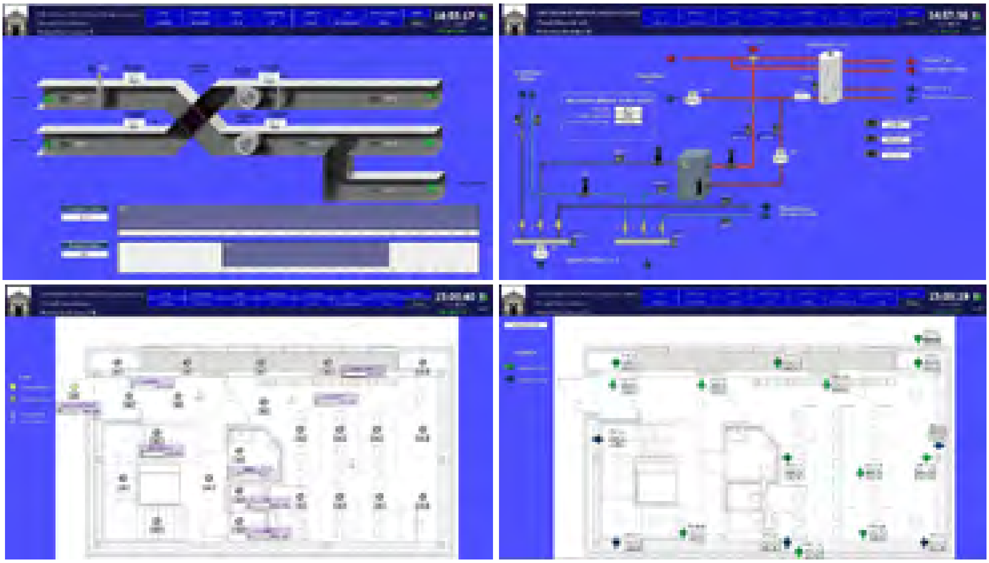

Figure 2. Web-interface of BMS system – monitoring system panels: vetilation; heat pump division; floor plan with lighting control and RHT measurement.

the existing state and for the predicted state, with the determination of the savings indicator for a given solution, resulting from a comparison of both states. The assessment results are presented in Table 2

3. CONCLUSIONS.

To determine the effect of improving the existing system, the standard recommends using a detailed method based on energy flow simulation, but it also allows for the use of a simplified method based on indicators for preliminary determination of improvement potential and as a preliminary tool for determining savings. The installations in the building were designed for research purposes and not all of them are used by BACS to increase the energy efficiency of the building. The presentation of calculations of possible savings based on the simplified index method used was abandoned due to the high discrepancy between the results and the measurements taken in some research fields in the building. Although the index method is recommended for estimating savings for designed buildings, its simplicity and ease of use encourage further research to determine its accuracy more precisely.

A summary of all available and recorded data on building operation enables a holistic approach to building control. Data obtained by sensors from one installation can be correlated with the operation of other installations. Data on the status of all installations, combined with the recording of energy and energy carrier consumption, enables the generation of trends in building use and energy consumption, which forms the basis for the implementation of prediction algorithms that increase the efficiency of energy storage and the use of periodically available renewable energy. An assessment of the automation system allowed us to identify the dependencies between the measured environmental parameters, the operating status of a given system, and the operational requirements of other systems. Two particularly important points were identified: the need to monitor user activities in order to optimize the operation of the installation providing comfort, and external weather conditions in order to plan better use of solar energy storage systems..

ANNEX

Table 1. BMS inventory in the LEEARE building.
Abbreviations used:
TABS – Thermal Activated Building System – a system for distributing and accumulating solar heat in a building, collected in the space of the double glass façade of the building.
[b] the value in brackets () refers to the number of measured parameters recorded by the BMS, the value outside the brackets refers to the number of mounted measuring devices.
[and] TABS – (*thermal activated building system*) in the LEEARE building, which is a building system consisting of a double glass façade, space and channels for active distribution of warm air around the accumulation mass constituting a massive structure of the building.

1	2	3	4	5	6	7	8
No.	measure-ment	Designa-tion	protocol	pcs.	unit	registra-tion	Area, location / comments Comments
1.	Central system						
1.1.	Room air tempera-ture	Heating, research	MOD-BUS RTU	44	oc	Contin-uous, 15 min interval.	All rooms, gradient in selected rooms, outdoor
1.2.	TABS air tempera-ture a	Warm air dis-tribution system	MOD-BUS RTU	44	oc	Contin-uous, 15 min interval.	Spaces of the dou-ble glass façade and ventilation void around the struc-tural accumulation mass
1.3.	TABS ground tempera-ture	Research	MOD-BUS RTU	11	oc	Contin-uous, 15 min interval.	Ground under the building and side slope

1.4.	RHT - relative humidity and air temperature	Research	MODBUS RTU	19 (38)b	oc /%	Continuous, 15 min interval.	All rooms, 2 pcs. on the façade
1.5.	RHT - Relative Humidity and Air Temperature TABS	Research	MODBUS RTU	46 (92)	oc /%	Continuous, 15 min interval.	Spaces of the double glass façade and ventilation void around the structural storage mass, under the roof, ducts in the ceiling and under the building
1.6.	Irradiance	Lighting, research	analog	2	W/m2	Continuous, 15 min interval.	Inside the teaching room, on the façade, on the surface of the walls
1.7.	CO2 / temp.	Ventilation, research	MODBUS RTU	5 (10)	ppm/oc	Continuous, 15 min interval.	Inside all rooms for people, on internal walls
1.8.	Air Speed TABS	Ventilation, research	analog	13	m/s	Continuous, interval 5 min.	Spaces of double glass façade and ventilation void around the structural storage mass, under the roof
2.	Ventilation installation						
2.1.	Air temperature – ventilation ground exchanger	Ventilation, research	MODBUS RTU	17	oc	Continuous, 15 min interval.	Inside the ventilation ducts of the ground heat exchanger/ 30% damaged or giving incorrect readings

2.2.	Air temperature – ventilation system	ventilation / research	MODBUS RTU, analog	18	oc	Continuous, interval 5 min.	Inside the ventilation ducts
2.3.	Air Flow Velocity – Ventilation Installation	ventilation / research	MODBUS RTU	11	m/s	Continuous, 15 min interval.	Inside the ventilation ducts – all entrances and exits from the air handling units
2.4.	Throttle status	ventilation / research	analog	4	on/off	Change of state	Duct dampers
2.5.	Condition of heater/ duct cooler valves	ventilation / research	analog	3	on/off	Change of state	Duct dampers
2.6.	Fan status TABS	TABS / Research	analog	8	%	Change of state	Double glass façade
	Throttle status TABS	TABS / Research	RF	10	on/off	Change of state	Double glass façade
3.	Heating, cooling and hot water installation						
3.1.	Medium temperature	heating, DHW, research	MODBUS RTU	36	oc	lack	Wires of all circuits – input and return
3.2.	Valve Status	heating, DHW, research	analog	15	on/off	Change of state	Distribution cables
1	2	3	4	5	6	7	8
3.3.	Heat meters	heating, DHW, research	M-BUS	14 (84)	GJ; In; m3/h; oc	Change of state	Distribution cables - all circuits - back
3.4.	Refrigerant flow counters	heating, DHW, research	M-BUS	4	m3	Continuous, 15 min interval.	Main distribution cables

3.5.	Circulator Pump Status	heating, DHW, research	analog	15 (30)	on/ off;	Change of state	Distribution cables - all circuits - back
4.	Ground temperature measurement system (vertical heat pump heat exchangers)						
4.1.	Ground temperature	Research	1-wire	28	oc	Continuous, 15 min interval.	Along production and research wells/ Measuring lines damaged
5.	Lighting installation						
5.1.	Light intensity/ presence sensor	Lighting/ research installation	KNX	14	Lx/ y/n	Continuous, interval 5 min.	Indoors, under the ceiling
5.2.	Lighting fixtures	Lighting installation	DALI	64 (128)	on/off , %	Change of state	Luminaires with adjustable intensity
6.	Meters						
6.1	OZE Analyzer	Electrical/ Research	MODBUS TCP	1 (6)	Kwh; V;A; Kw	Continuous, 15 min.	PV Installation, Wind Turbine
6.2.	Electricity meters	Electrical/ Research	MODBUS RTU	19	Kwh	Continuous, 15 min interval.	Installation circuits / Division of circuits inconsistent with the division of heat and lighting distribution
6.3.	Water meters	Plumbing / grey water	M-BUS	7	m3	Continuous, 15 min interval.	Installation circuits
6.4.	Grey water level	grey water	analog	1	%	Continuous, 15 min interval.	Underground rainwater tank
7.	Sunshades						
7.1	External roller shutters	Solar shields, TABS	230V, DI	16	On/ off	Change of state	External glazing/ Blocked by climbing plants,

7.2.	Window actuators	Windows, ventilation system	230V, DI	7	On/ off	Change of state	Exterior and interior windows – double glass façade / No indication of the degree of window opening
7.3.	Interior blinds	Solar shields, TABS	RF	16	On/ off	lack	Interior of the glass double façade/ No indication of the blind opening status
8.	Meteo Station	BMS, Research	RF (DAVIS)	1		Continuous, interval 5 min.	Roof of the building/ Radio connection sensitive to interference
8.1.	Wind speed				m/s,		
8.2.	Atmospheric pressure				hPa		
8.3.	Dew Point				oC		
8.4.	RH ext				%		
8.5.	Precipitation Alarm				1/0		
8.6.	Opad Rain Rate				mm		
8.7.	Irradiance				W/ m2		
8.8.	External temperature				oC		
8.9.	UV index				n		
8.10.	Wind direction				is		
Together:				460 (640)b			

Table 2. Designation of automation efficiency classes in the LEEARE building for the existing (E) and expected (P) state. The table shows only the fields relevant to the conducted research and omits the fields that are not applicable to the analysis.

Abbreviations used in the table:

H	heating
DHW	Domestic Hot Water
the	auxiliary (electricity)
L	lighting (electricity)
OHC	Overall for Heating and Cooling
OE	Overall for electric energy

1	2	3	4	5	6	7
Lp./ E (existing) P (projected)	Level	Automatic control	Class	system type	Efficiency factor	energy saving factor
1.		Heating control				
1.1.		Emission control				
		The control function is applied to the heat emiter		H		1
E	3	Individual modulation room control with communication	A		0,8	
P	4	Individual modulation room control with communication with occupancy detection	A		0,8	
1.2.		Emission control for TABS		H		1
E	2	Advanced central automatic control	A		0,8	
P	3	Advanced central automatic control with intermittent operation and temperature feedback control	A		0,8	

1.3.		Control of distribution pumps in networks		H		0,8
E	1	Outside temperature compensated control	C		1	
P	2	Demand based control	A		0,8	
1.4.		Control of distribution pumps can be installed at different levels in the network		H		1
1.4a		The controlled pumps can be installed at different levels in the network		H		1
E	3	Variable speed pump control	B		0,88	
P	2	Balanced statically per emitter, and a static group balance	D			1
1.5		Intermittent control of emission and/ or distribution		H		0,8
E	1	Automatic control with fixed time program	C		1	
P	3	Automatic control with demand evaluation	A		0,8	
1.7		Heat generator control (combustion and distect heating)		H		N/A
1.8		Heat generator control (outdoor unit)		H		N/A
1.9		Sequencing of different heat generators		H		0,67
E	0	Priorities only based on run- fling time	D		1,2	
P	3	Control accordingto prediction based dynamic priority list	A		0,8	
1.10		Control of thermal energy storage (TES) operation				0,67
E	0	Continuous storage operation	D	H	1,2	
P	2	Load prediction-based storage operation	A		0,8	
2.1.		Control of DHW storage charging with direct electric heating or integrat-ed electric heat pump		DHW		N/A

2.2.		Control of DHW storage charging using hot water generation		DHW		N/A
2.3.		Control of DHW storage charging with solar collector and supplementary heat generation		DHW		N/A
2.4.		Control of DHW circulation pump		DHW		0,72
E	0	No control, continuous operation	D		1,11	
P	1	With time program	A		0,8	
4.1.		Ventilation and air-conditioning control		the		0,85
E	1	Time control	B		0,87	
P	3	Demand based control	A		0,74	
4.2		Room air temperature control		the		0,66
E	0	On-off control	D		1,12	
P	2	Optimized control	A		0,74	
4.3		Room air temperature control (Combined air-water systems)		the		0,66
E	0	No coordination	D		1,12	
P	1	Coordination	A		0,74	
4.4		Outside air (OA) flow control				N/A
1	2	3	4	5	6	7
4.5		Air flow or pressure control at the air handler level		the		0,74
E	1	On off time control	C		1	
P	4	Automatic flow or pressure control (with reset)	A		0,74	
4.6		Heat recovery control: icing protection	VGWC, no available icing			N/A

4.7		Heat recovery control: prevention of overheating	VGWC, no available overheating			N/A
4.8		Free mechanical cooling		the	passive cooling	N/A
4.9		Supply air temperature control		the		0,78
E	0	No automatic control	D		1,12	
P	2	Variable setpoint with outside temperature compensation	B		0,87	
4.10		Humidity control		the		0,78
E	0	No automatic control	D		1,12	
P	2	Direct humidity control	A		0,87	
5.		Lighting control				
5.1		Occupancy control		L		0,76
E	1	Manual on/off switch + additional sweeping extinction signal	C		1	
P	3	Automatic detection (manual on)b	A		0,76	
5.2		Light level/daylight control		L		0,76
E	0	Manual (central)	C		1	
P	3	Automatic dimming b	A		0,76	
6.		Blind control		L		0,69
E	1	Motorized operation with manual control	D		1,1	
P	3	Combined light/blind/HVAC control	A		0,76	
7.		Technical home and building management				
7.1		Setpoint management		OHC		0,67
E	0	Manual setting room by room individually	D		1,2	

P	3	Adaptation from a central room with frequent set back of user inputs	A		0,8	
7.2		Runtime management		OHC		0,80
E	1	Individual setting following a pre-defined time schedule including fixed preconditioning phases	C		1	
P	2	Individual setting following a pre-defined time schedule; adaptation from a central room; variable preconditioning phases	A		0,8	
7.3		Detecting faults of technical building systems and providing support to tl e diagnosis of these faults		OHC		0,80
E	1	With central indication of dectected faults and alarms	C		1	
P	2	With central indication of detected faults and alarms/diagnosing functions	A		0,8	
7.4		Reporting information regarding energy consumption, indoor conditions		OHC		0,80
E	0	Indication of actual values only (e.g. temperatures, meter values)	C		1	
P	2	Analysing, performance eval- uation, benchmarking	A		0,8	
7.5		Local energy production and renewable energies		OHC		0,80
E	0	Uncontrolled generation de- pending on the fluctuating availability of RES and or run time of CHP; overproduction will be fed into the grid.	C		1	
P	1	Coordination of local RES and CHP with regard to local energy demand profile including energy storage management optimization of own consumption	A		0,8	
7.6		Waste heat recovery and heat shifting		OHC		1,00

E	0	Instantaneous use of waste heat or heat shifting	D		1,07	
7.7		Smart grid integration		OE		0,86
E	0	No harmonization between grid and building energy systems; building is operated independently from the grid load.	C		1	
P	1	Building energy systems are managed and operated depending on grid load demand side management is used for load shifting	A		0,86	

REFERENCES:

1 EN 15232-1:2017 Energy Performance of Buildings – Energy performance of buildings – Part 1: Impact of Building Automation, Controls and Building Management, CEN 2017

2 Fokaides, P.A.; Apanaviciene, R.; Cerneckiene, J.; Jurelionis, A.; Klumbyte, E.; Kriauciunaite-Neklejonoviene, V.; Pupeikis, D.; Rekus, D.; Sadauskiene, J.; Seduikyte, L.; et al. "Research Challenges and Advancements in the field of Sustainable Energy Technologies in the Built Environment". Sustainability 2020, 12, 8417.

3 Gilewski Paweł Grzegorz, Węglarz Arkadiusz, Janik Klaudia [et al.], "National Plan for Renovation of Buildings in Poland". Building Materials, 2025, No. 1, pp.51-54

4 Kwasnowski P.– "Template of tender specifications for technical installations of buildings and BACS, TBM and BMS systems: PN-EN 15232:2017 standard". Civil Engineer, No. 5/2022. https://inzynierbudownictwa.pl/wzorzec-specyfikacji-przetargowej-na-instalacje-techniczne-budynkow-oraz-systemy-bacs-tbm-i-bms-norma-pn-en-152322017/

5 Lu Wan, Xiaobing Dai, Torsten Welfonder, Ekaterina Petrova, Pieter Pauwels – "Semi-automated Thermal Envelope Model Setup for Adaptive Model

Predictive Control with Event-triggered System Identification" Conference Paper · September 2023, DOI: 10.26868/25222708.2023.1611
6 Morkunaite L., Pupeikis D., Jurelionis A, Fokaides P. A., Papadopoulos "An Analytical Model for the Impact of Building Control and Automation Upgrade on Space Heating Energy Efficiency". Buildings 2022, 12, 1074. https://doi.org/10.3390/buildings12081074
7 Ozadowicz, A.; Grela, J. "Impact of building automation control systems on energy efficiency—University building case study". In Proceedings of the 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, 12 September 2017
8 PN-EN ISO 52120-1:2022 "Energy performance of buildings. The contribution of automation, control and technical management of buildings. Part 1: General structure and procedures".
9 Shuo Chen a, Guomin Zhang a, Xiaobo Xia b, Sujeeva Setunge a, Long Shi. "A review of internal and external influencing factors on energy efficiency design of buildings". Energy and Buildings, Volume 216, 1 June 2020, 109944. https://doi.org/10.1016/j.enbuild.2020.109944
10 Turecki Adam. Budynek „Laboratorium Architektury Energooszczędnej i Energii Odnawialnych" Wydziału Architektury Politechniki Białostockiej. Białystok 2016. Architecturae et Artibus, ISSN 2080-963811
11 Turecki Adam Kazimierz, Tur Marcin, Czarnecki Bartosz [i in.] – „Renovation of modernist housing developments in the pursuit of modernity for well-being and clean energy". Energies, ISSN , e-ISSN 1996-1073
12 Węglarz A., Gilewski P. G., Ogrodniczuk j., Zdanowski P., Żurawski J., Rajkiewicz A., Rajkiewicz K., Twardowski J., Symela K., Woźniak I., Kus J.– "Strategy for meeting the demand for qualified employees in energy-efficient construction by 2030". National Energy Conservation Agency S.A., Warsaw 2024.

DIGITAL TECHNOLOGIES IN ARCHITECTURE: PARAMETRIC DESIGN AND BIM IN THE SERVICE OF PRESERVING ARCHITECTURAL HERITAGE

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ABSTRACT:

In modern cultural heritage preservation, digital technologies play a key role in documentation, restoration, and analysis of historical structures. This paper explores the application of HBIM (Heritage Building Information Modeling) models, parametric design, and BIM technology in the conservation of architectural heritage, examining the capabilities and limitations of these methods in restoring structures with unique characteristics. Digital tools enable precise documentation of existing conditions, providing a foundation for planning restoration interventions and repairs. Examples of 3D scanning, photogrammetry, and other digital methods for reconstructing architectural elements are presented. HBIM models offer a deeper understanding of material and structural characteristics, aiding decision-making during restoration. However, challenges include standardizing procedures, adapting technologies to the specific needs of historical buildings, and the need for individualized approaches due to their complexity. Digitalization enhances conservation practices and enables better interpretation and presentation of cultural heritage through interactive models and visualizations. The paper analyzes the technical, financial, and ethical aspects of digitalization, including the alignment of digital models with legal norms that vary between countries. HBIM models provide high precision in reconstruction and structural risk analysis, contributing to safer restoration planning. Moreover, digitalization allows for the virtual reconstruction of damaged or destroyed parts of heritage, ensuring their sustainability and wider public accessibility. The importance of developing methodological frameworks to preserve the authenticity of digital models and integrating new tools with traditional restoration methods is emphasized. While digital tools increase restoration efficiency and precision, there is a need to further develop technologies that bridge modern methods with traditional conservation techniques. The continued advancement of HBIM can contribute to preserving historical structures, making them valuable for education, research, and cultural heritage presentations while maintaining their authenticity and historical value. Collaboration among experts in architecture, conservation, engineering, and information technology is crucial for the successful implementation of digital tools in cultural heritage preservation.

Keywords: Cultural heritage, digital technologies, HBIM, photogrammetry, conservation, virtual reconstruction.

1. INTRODUCTION

The digital revolution in architecture, driven by advances in computer technologies and software tools, has significantly changed the way architects approach the design process. Parametric design and Building Information Modeling (BIM) are key innovations that enable architects to engage with more complex forms and more precise planning. Parametric design allows for the creation of dynamic forms that can be easily adjusted according to various input parameters, which significantly accelerates the design process and enables greater creativity (Kolarević, 2003). On the other hand, BIM represents a digital model that integrates all information about a building structure, allowing for better coordination between different disciplines, from design to construction (Eastman et al., 2011). Through these technologies, the architectural process becomes more automated, precise, and integrated, which has a significant impact on all aspects of architectural practice.

Scientific works such as BIM Handbook (Eastman et al., 2011) and Architecture in the Digital Age (Kolarević, 2003) thoroughly explore how these technologies are transforming the design and construction of buildings, as well as how they contribute to greater sustainability and the preservation of cultural heritage. Although these technologies have primarily been used in new construction, their application in the restoration and renovation of cultural heritage structures is increasingly being explored. Parametric design, with its ability to create adaptive forms, and BIM, with its capacity to manage large amounts of data, represent key technologies that can enhance the preservation of cultural heritage in a contemporary context.

1.1. Research Subject:

The subject of this research is the application of digital technologies, with a particular focus on parametric design and Building Information Modeling (BIM), in contemporary architectural practice. The aim is to explore how these technologies shape architectural processes, enhance design, and enable more efficient resolution of complex design problems. The research will focus on analyzing the impact of parametric design and BIM on the creative processes in architecture and on how these technologies transform the way architects approach space, form, and function.

1.2. Research Objectives:

To investigate the role of parametric design and BIM in contemporary architecture – how these technologies enable greater precision in design and efficiency in the realization of architectural projects.

To analyze the influence of digital tools on architects' creative processes – how parametric design and BIM affect the way space, form, and function are conceptualized in architecture.

To examine the application of parametric design and BIM in sustainability and the preservation of cultural heritage – how these technologies can be used in the context of architectural monuments and cultural structures.

To explore the challenges and opportunities these technologies offer in the process of digital fabrication and construction.

1.3. Research Methods:

The research will use a combination of qualitative and quantitative methods. The main methods to be applied include:

Literature analysis – studying relevant books, academic papers, and professional articles that address parametric design and BIM, as well as their applications in architecture. Relevant literature includes works such as Menges (2012) and Eastman et al. (2011), which provide a detailed overview of these technologies in contemporary architectural practice (Menges, 2012), (Eastman et al.,2011).

Case studies – analyzing specific examples from architecture and the construction industry where parametric design and BIM have been successfully applied. These examples will help in understanding the challenges, advantages, and possibilities these technologies bring to practice.

2. THEORETICAL FRAMEWORK

The development of digital technologies in architectural design has enabled the integration of parametric design and Building Information Modeling (BIM) systems, thereby transforming the way architectural projects are shaped and managed. This theoretical framework encompasses the key concepts and methods within parametric design, BIM, and their application in architecture and the preservation of cultural heritage.

Parametric Design – Definition and Significance

Parametric design represents a design methodology in which the geometry of objects is generated through a set of defined parameters and algorithms, allowing dynamic form changes depending on variable inputs (Kolarević, 2003). This approach differs from traditional design because it enables generative modeling, where the designer sets rules instead of directly drawing forms (Menges, 2012). Through parametric design, it is possible to explore complex forms, optimize material consumption, and improve construction efficiency. For example, research shows that optimization algorithms can significantly enhance the structural performance and sustainability of buildings (Oxman, 2010). These methods are increasingly used in experimental architecture, but also in restoration, where they enable precise digital reconstruction of historical structures (Dore & Murphy, 2017).

Building Information Modeling (BIM)

BIM represents a systematic approach to the digital modeling of buildings and infrastructure, integrating data on geometry, materials, structural characteristics, and construction processes (Eastman et al., 2011). Unlike traditional CAD models that focus on geometric representations, BIM integrates information that enables performance analysis throughout the entire life cycle of a building. One of the key aspects of BIM is interoperability, i.e., the possibility for collaboration among various disciplines within a single digital model. This is particularly important in heritage restoration, where BIM allows precise documentation of the object's condition and simulation of conservation interventions (Volk et al., 2014).

2.1. Application of Parametric Design and BIM in Architectural Heritage

The use of digital technologies in the protection and restoration of cultural heritage is becoming increasingly relevant, as it allows precise documentation and planning of conservation work. Parametric design can play a key role in generating digital reconstructions, while BIM enables the systematization of data and analysis of different protection scenarios (Dore & Murphy, 2017).

Key application examples include:
Digitization of architectural heritage – scanning historic buildings and converting them into BIM models containing data on materials and structural conditions (Volk et al., 2014).

Restoration through parametric design – algorithmic generation of missing façade parts and structures based on historical data.
Simulation of future interventions – using BIM models to analyze potential impacts of conservation work on the stability and authenticity of the building.
The integration of parametric design and BIM into architectural practice not only enhances creative processes and design efficiency, but also enables new methods of research and preservation of cultural heritage. Modern technologies provide tools for form optimization, digitalization of historical buildings, and the improvement of interdisciplinary collaboration in the construction industry. This theoretical framework lays the foundation for further analysis of concrete examples and case studies, which will provide a deeper understanding of the role of digital technologies in architecture and heritage conservation.

Table 1. Synthesis of Digital Technologies

Section	Description
Parametric Design	A methodology that uses parameters and algorithms to generate geometric forms, allowing dynamic changes in design.
Advantages of Parametric Design	Enables exploration of complex forms, optimization of material consumption, and improvement of structural performance.
Application in Architecture and Restoration	Provides the possibility of digitally reconstructing historical objects through generative modeling.
Building Information Modeling (BIM)	A digital approach to modeling buildings that integrates all necessary data for performance analysis throughout the object's life cycle.

3. INTRODUCTION TO PARAMETRIC DESIGN AND ITS RELEVANCE IN HERITAGE CONSERVATION

Parametric design represents a contemporary methodological approach that combines algorithmic logic with digital modeling to describe, analyze, and manipulate complex architectural forms. In the context of heritage conservation, this method provides precise and adaptable tools for the digital reconstruction, documentation, and simulation of interventions on historical structures. By using variable parameters and rule-based modeling, professionals can explore multiple design solutions, maintain geometric accuracy, and ensure the reversibility of interventions. The integration of parametric design with Building Information Modeling (BIM), especially in the form of Heritage BIM (HBIM), enhances collaborative workflows, data integration, and decision-making processes. As a result, parametric design contributes significantly to the sustainable and informed conservation of architectural heritage.

3.1. Case Studies: Applications of Parametric Design in Architectural Heritage Conservation

A 2022 study published by MDPI demonstrates how the parametric modeling of massive vaults is incorporated into HBIM (Heritage Building Information Modeling), enabling LOD 500 and real-time fine-tuning of geometry based on laser scanning, field measurements, and photogrammetry. This provides highly accurate digital replicas and reliable foundations for restoration work.

In a 2023 follow-up, MDPI presents the implementation of the "E-PUSH" algorithmic tool to assess the seismic stability of existing walls within a parametric HBIM workflow. This is demonstrated in the case of the Bernardo Rucellai School in Florence.

Luis Carlos Cruz-Ramírez (2019) illustrates the use of parametric modeling in the restoration of the Ex-Oratory of San Filippo de Neri dome in Bologna. The algorithm, based on mathematical domain definitions, enabled the restoration team to develop a precise parametric model prior to constructing the new structure (Cruz-Ramirez, 2019).

Studies such as *Thinking Parametric Design* by Hernández (2006) describe the development of Gaudí's columns through the superimposition of two helicoidal rotations—a concept that was later implemented through CNC machining of stone elements (Hernandez, 2006).

The report *Structural Stone in Sagrada Família* confirms the use of parametric modeling today in the CNC processing of pre-fabricated stone panels that are installed on-site.

Tryfonos et al. (2021) present a methodology for adaptive parametric documentation of medieval structures such as the Asinou Church and Kolossi Castle. These case studies integrate 3D scanning data with parametric design and BIM to create a loop of metadata exchange between heritage stewards and restoration professionals (Tryfonos et al., 2021).

Ni et al. (2024) describe how a parametric digital twin was developed for Löfstad Castle in Sweden. The model integrates real-time sensor data to monitor microclimate conditions such as air quality, temperature, and humidity—establishing a sustainable framework for environmental heritage conservation (Ni et al., 2024).

Altun et al. (2022) demonstrate how parametric design rules and photogrammetry were used to digitally reconstruct Ottoman ceramic elements, such as historical wall surfaces. These models can be used for replica generation and series production in restoration efforts (Altun et al., 2022).

The HBIM workflow integrates geometry (via BIM), algorithmic logic (visual programming in Grasshopper), and on-site data collection.

It allows for simulations—seismic, climate-based, structural—and enables interactive modification of restoration strategies, making parametric design a highly adaptive and interdisciplinary tool in heritage protection.

Figure 1. Reconstruction of the church of Santa Clara, Naples Intervention by contrast. Photography by L. C. Cruz Ramírez 2017.

Figure 1. Reconstruction of the church of Santa Clara, Naples.Intervention by contrast. Photography by L. C. Cruz Ramirez 2017. Source: Cruz-Ramírez, L. C. Parametric Design in Restoration Project, (2019).

Figure 2. Parametric construction of pendentives and dome by Boolean operation. Made by L. C. Cruz Ramirez, 2018. Source: Cruz-Ramírez, L. C. Parametric Design in Restoration Project, (2019).

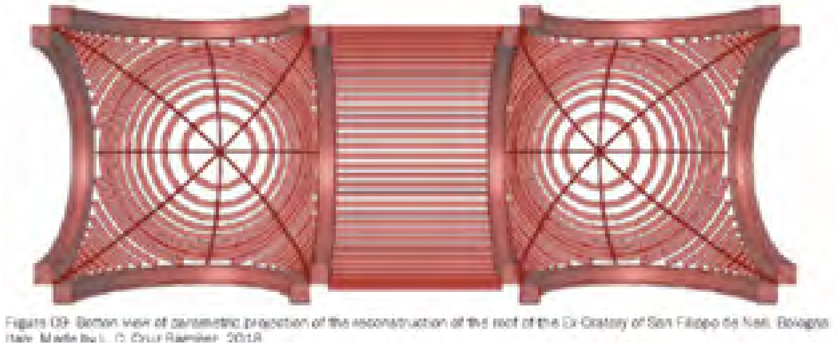

Figure 3. Botton view of parametric projection of the reconstruction of the roof of the Ex-Oratory of San Filippo de Neri, Bologna. Made by L. C. Cruz Ramirez, 2018. Source: Cruz-Ramírez, L. C. Parametric Design in Restoration Project, (2019).

3.2. Advantages and Challenges of Applying Parametric Design in Heritage Conservation

This subsection offers a critical examination of the technology and its application. It is recommended to divide the analysis into advantages, challenges, and future development perspectives.

Advantages:

High precision and efficiency: Parametric design enables accurate modeling and documentation, particularly when combined with HBIM and 3D scanning techniques.

Interactive models for interdisciplinary collaboration: Parametric tools foster cooperation between architects, conservators, engineers, and historians through shared visual models and simulation platforms.

Flexible modification and design variation: Enables the simulation of different restoration scenarios, allowing comparative analysis and informed decision-making.

Compatibility with CNC and 3D printing: Facilitates the digital fabrication of replacement components with geometric accuracy, preserving structural integrity.

Challenges and Limitations:

Requires advanced technical expertise: Knowledge of programming and visual scripting tools (e.g., Grasshopper) is essential, posing a barrier for many heritage professionals.

Risk of losing authenticity: Automated or generative processes may compromise historical integrity if not grounded in thorough contextual understanding.

Lack of standardized protocols: Parametric design is not yet fully integrated into official conservation guidelines or methodologies in many countries.

Software and hardware demands: High-resolution scanning, BIM platforms, and computational resources are often required, which can limit accessibility and scalability.

Future Development Perspectives:

Integration with artificial intelligence and machine learning: For automatic recognition of stylistic features and damage detection, enabling predictive conservation strategies.

Multisensor parametric digital twins: For continuous monitoring of environmental conditions, structural behavior, and material degradation in heritage buildings.

Stronger presence in conservation education and policy: Expanding the inclusion of parametric methods in academic curricula and national heritage strategies will help institutionalize their use.

4. DOCUMENTATION AND ANALYSIS OF HISTORICAL BUILDINGS USING DIGITAL MODELS

The development of digital technologies has significantly improved the documentation and analysis of historical buildings, enabling precise modeling, reconstruction, and visualization of cultural heritage. Traditional documentation methods, such as hand drawings and 2D photographs, are often insufficient for a complete understanding of the complex structures of historic buildings. With the advent of 3D scanning, photogrammetry, Building Information Modeling (BIM), and Historic Building Information Modeling (HBIM), it is now possible to preserve and analyze cultural heritage more accurately (Murphy et al., 2009).

Digital Documentation Methods

3D scanning uses laser technology to accurately map the surfaces of objects in three dimensions. This technique enables the creation of precise digital models that can be used for building condition analysis, damage monitoring, and restoration planning. Photogrammetry, which uses a series of photographs taken from various angles to reconstruct a 3D model of the object, has also proven to be a powerful tool in architectural heritage documentation (Remondino & Campana, 2014). A particularly significant method is Historic Building Information Modeling (HBIM), which enables the creation of detailed digital models of historical buildings with integrated data on materials, construction, and restoration interventions (Dore & Murphy, 2017). These models not only document the current state of buildings but also allow prediction of future damage through simulations and data analysis (Volk, Stengel & Schultmann, 2014).

In addition to static documentation, digital models can include semantic information, enabling more precise analysis of historical elements of the building, such as materials used in different periods and the impact of weather conditions on the degradation of the structures (López et al., 2018). The use of artificial intelligence and machine learning further enhances the analysis process, enabling automated recognition and classification of architectural elements based on existing data.

Application in Conservation and Restoration

One of the key advantages of digital documentation is the ability to track changes to historical buildings over time. For example, HBIM models can be used to compare the current and previous state of an object, allowing for precise restoration planning (Murphy et al., 2009). These technologies are especially useful for documenting endangered monuments, automated detection of material degradation, and developing protection strategies through digital archives and databases (Dore & Murphy, 2017). In addition, digital models enable virtual reconstruction of destroyed or partially preserved structures. Using data from historical sources, researchers can reconstruct the original appearance of buildings, thus contributing to their preservation and promotion through digital platforms or interactive museum exhibitions (Remondino & Campana, 2014).

The integration of digital methods in the documentation and analysis of historical buildings represents a significant advancement in the field of cultural heritage protection. The combination of 3D scanning, photogrammetry, HBIM models, and artificial intelligence allows for precise analysis and long-term monument protection while providing researchers with new tools to understand architectural development through history. Using these methods, conservation strategies can be improved, enabling more efficient protection and restoration of valuable cultural assets.

4.1. HBIM – Specific Methods for Cultural Heritage

Heritage Building Information Modeling (HBIM) is a specialized approach for the digital documentation and analysis of historical buildings. HBIM is developed based on data collected through laser scanning, photogrammetry, or UAVs (unmanned aerial vehicles), after which parametric 3D models are created that allow for detailed study and reconstruction of structures (Murphy et al., 2011). One of the main challenges in HBIM is modeling complex historical structures that were often not built according to modern architectural standards. To overcome this issue, advanced algorithms are being developed to generate libraries of historical architectural elements, allowing for accurate reconstruction in the digital space.

The use of HBIM in cultural heritage protection offers several advantages:

- Enables precise monitoring of changes in buildings over time
- Enhances the integration of various data types, including historical drawings, textual archives, and in-situ material analyses
- Allows digital reconstruction of destroyed or damaged parts of buildings
- Facilitates collaboration between architects, art historians, conservators, and engineers
- Additionally, HBIM models can be integrated with GIS systems to enable spatial analysis of cultural heritage at urban and regional levels (Dore & Murphy, 2020)

4.2. Restoration and Reconstruction with Digital Tools

The application of digital tools in the restoration and reconstruction of historical buildings encompasses a wide range of technologies, including

3D scanning, HBIM, virtual and augmented reality (VR/AR), AI-based material analysis, and digital fabrication (Remondino et al., 2019). These technologies enable precise identification of damage and planning of appropriate restoration interventions.

3D Scanning and HBIM in Restoration

3D scanning methods, such as LiDAR and Structure-from-Motion (SfM) photogrammetry, allow for the acquisition of precise digital models that are later used in HBIM systems. These models serve to analyze structural stability, predict future damage, and plan restoration works (Bruno & Roncella, 2020).

Artificial Intelligence in Damage Analysis

Artificial intelligence enables automated damage recognition, classification of degraded materials, and prediction of future problems based on weather and structural factors. For example, deep learning algorithms can analyze photographic and thermal images of historic buildings to detect cracks, moisture, or other forms of degradation.

Virtual and Augmented Reality in Reconstruction

VR and AR technologies allow for the digital reconstruction of lost building elements and testing of various approaches before physical restoration begins. This is especially useful in cases where complex architectural elements must be reconstructed based on fragmentary data. In combination with HBIM systems, digital technologies enable more efficient and precise management of restoration and conservation processes for cultural heritage, making them more sustainable and cost-effective.

4.3. Implementation

The application of digital technologies in cultural heritage preservation is illustrated through several significant projects. For example, Heritage Building Information Modeling (HBIM) allows the creation of interactive models that contain and manage data about architecturally valuable buildings. These models include geometric information and physical properties of elements, such as dimensions and materials, which facilitate restoration and maintenance planning.

Another example is the digitization of cultural heritage in Serbia, where guidelines have been developed for conducting the digitization process, taking into account best practices and international standards. These guidelines define steps for digitizing cultural heritage, including the involvement of professionals and external collaborators, with the goal of protecting and promoting cultural heritage (Guide to Digitalization).

Table 2. Method and Use of Digital Documentation

Digital Documentation Method	Description	Use in Conservation and Restoration
3D Scanning	Uses laser technology to precisely map objects in three dimensions.	Creating accurate digital models, monitoring damage, and planning restoration.
Photogrammetry	Uses photographs taken from different angles to reconstruct a 3D model.	Precise documentation of architectural heritage.
HBIM (Heritage Building Information Modeling)	Creates digital models of historical buildings with data on materials, construction, and restoration.	Detailed analysis of objects, monitoring changes, and reconstructing destroyed parts.
Artificial Intelligence (AI)	Automatic recognition and classification of damage based on data.	Analyzing material degradation, predicting damage, and improving protection strategies.
VR/AR (Virtual and Augmented Reality)	Creates virtual reconstructions and simulations of objects.	Digital reconstruction of destroyed parts, testing restoration interventions.

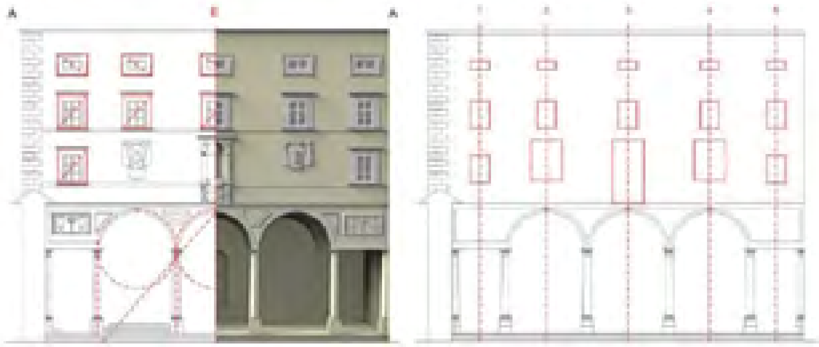

Figure 4. Application of the HBIM process. Source: https://www.gradnja.rs/wp-content/uploads/2020/10/hbim-arhitektonsko-nasledje.jpg

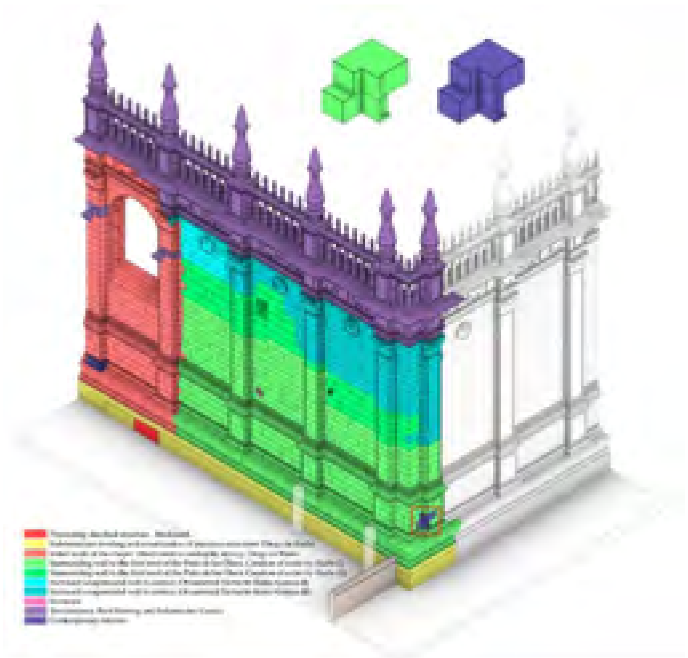

Figure 5. Process of reverse modeling of an architectural object. Source: https://www.gradnja.rs/wp-content/uploads/2020/10/3.jpg

5. CHALLENGES AND LIMITATIONS

The implementation of digital technologies in the field of cultural heritage brings significant advantages but also faces numerous challenges. These challenges include technical and financial aspects, the need for standardization of methods, as well as ethical issues related to digitization and the preservation of the authenticity of architectural objects.

Technical and Financial Implementation Challenges

One of the main challenges in the digitization of cultural heritage is the high cost of acquiring and maintaining specialized equipment and software. For example, high-quality 3D scanners and data processing software packages require significant financial investment. Additionally, continuous training of experts to work with these technologies is necessary, which further burdens the budgets of institutions responsible for cultural heritage preservation. In Serbia, the digitization process is regulated by the Rulebook on Detailed Conditions for Digitizing Cultural Heritage, which defines the standards and procedures for this process (Guide to Digitalization).

Standardization of Methods and Adaptation to Cultural Heritage Specifics

The lack of universal standards for the digitization of cultural heritage can lead to inconsistent approaches and hinder data exchange between institutions. In Serbia, Guidelines for the Digitization of Cultural Heritage have been adopted, providing detailed procedures and best practices for creating digital versions of cultural assets, including the development of digital catalogs and long-term preservation of digitized heritage. However, adapting these standards to the specific needs of different types of cultural heritage remains a challenge (Guide to Digitalization).

Ethics of Digitization and the Authenticity of Architectural Objects

The digitization of cultural heritage raises ethical questions about the preservation of authenticity. The use of new technologies, especially artificial intelligence systems, brings innovative ways to protect and preserve cultural heritage but also introduces new risks, including legal and ethical issues. It is crucial to ensure that digital replicas faithfully represent the original objects and that intellectual property rights are respected, to avoid potential misuse or misinterpretation of cultural heritage (Regulation on Detailed Conditions for the Digitization of Cultural Heritage).

6. CONCLUSION

Digital technologies, including HBIM (Historic Building Information Modeling), parametric design, and BIM (Building Information Modeling) models, play a key role in the documentation, restoration, and analysis of historical objects. Their application enables precise recording, modeling, and analysis of architectural heritage, contributing to more efficient protection, preservation, and restoration of cultural assets. The advancement of heritage digitization not only improves the quality of documentation but also allows for a deeper understanding of historical structures through detailed analysis of materials, construction systems, and degradation processes. The use of digital tools in restoration and conservation processes opens up new possibilities for interactive interpretation of the past, including virtual reconstructions, augmented and virtual reality, as well as digital archives accessible to the public and researchers. However, alongside numerous advantages, the implementation of these technologies also brings several challenges, particularly in terms of technical execution, high implementation and maintenance costs, and ethical aspects related to the authenticity and interpretation of historical data. Case study analysis has shown that successful digitization of historical objects requires the integration of various methods, with HBIM playing a central role in consolidating data from different sources, enabling systematic management of the restoration process and long-term preservation of objects. However, the analysis of challenges indicates that further improvement in the standardization of methods is necessary to enhance the compatibility of digital models and adapt them to the specifics of cultural heritage. In addition to technical and financial obstacles, a key issue remains the ethical application of digitization – ensuring that digital models faithfully represent original objects without compromising their authenticity and historical integrity. In the future, the further development of digital tools for cultural heritage protection and management will require a multidisciplinary approach, involving collaboration among experts from architecture, engineering, archaeology, computer science, and conservation. It is also necessary to align with international standards to ensure data interoperability and the long-term sustainability of digital models. A particular challenge is the automation of documentation and restoration processes, where more efficient methods need to be developed for generating, updating, and archiving digital data. Continued progress in this field is expected to significantly contribute to the better preservation of historical objects, their accessibility to researchers and the broader public, as well as enriching cultural heritage for future generations.

7. LITERATURE:

Altun, S., et al. (2022) *Symmetry and Variance: Generative Parametric Modelling of Historical Brick Wall Patterns*, [online], http://dx.doi.org/10.48550/arXiv.2210.12856

Bogdanović, J., Krstić, D. and Turković, P. (2024) *Challenges and Ethical Aspects of Applying New Digital Technologies in Cultural Heritage*, [online],

https://dfest.nsk.hr/wp-content/uploads/2024/05/7_Bogdanovic-Krstic-Turkovic.pdf
Bruno, N. and Roncella, R. (2020) 'A restoration-oriented HBIM system for Cultural Heritage Documentation: The Case study of Parma Cathedral', [online], http://dx.doi.org/10.5194/isprs-archives-XLII-2-171-2018
Cruz-Ramírez, L.C. (2019) *Parametric Design in the Restoration Project*, [online], https://www.academia.edu/40025465/Parametric_design_in_the_restoration_project
Dore, C. and Murphy, M. (2017) 'Current State of the art Historic Building Information Modelling', *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, XLII-2/W5, pp. 185–192 , [online], http://dx.doi.org/10.5194/isprs-archives-XLII-2-W5-185-2017
Eastman, C., Teicholz, P., Sacks, R. and Lee, G. (2011) *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors and Facility Managers*, [online], Wiley, http://dx.doi.org/10.1002/9781119287568
Ministry of Culture and Information of the Republic of Serbia (2017) *Guidelines for Digitization of Cultural Heritage in the Republic of Serbia*, [online], https://www.europeanheritagehub.eu/document/smernice-za-digitalizaciju-kulturnog-nasledja-u-republici-srbiji-guidelines-for-the-digitisation-of-cultural-heritage-in-the-republic-of-serbia/
Hernández, C. (2006) *Thinking Parametric Design: Introducing Parametric Gaudi*, [online], http://dx.doi.org/10.1016/j.destud.2005.11.006
Kolarević, B. (2003) *Architecture in the Digital Age: Design and Manufacturing*, [online], Taylor & Francis, https://doi.org/10.4324/9780203634561
López, F.J., Lerones, P.M., Llamas, J., Gómez-García-Bermejo, J. and Zalama, E. (2018) 'A Review of Heritage Building Information Modeling (H-BIM)', *Multimodal Technologies and Interaction*, 2(2), 21, [online], http://dx.doi.org/10.3390/mti2020021

Menges, A. (2012) 'Material Computation: Higher Integration in Morphogenetic Design', *Architectural Design*, 82(2), pp. 14–21, [online], http://dx.doi.org/10.1002/ad.1374

Murphy, M., McGovern, E. and Pavia, S. (2009) 'Historic building information modelling (HBIM)', *Structural Survey*, 27(4), pp. 311–327, [online], http://dx.doi.org/10.1108/02630800910985108

Murphy, M., McGovern, E. and Pavia, S. (2011) 'Historic Building Information Modelling – Adding intelligence to laser and image based surveys of European classical architecture', *Automation in Construction*, 38, pp. 14–29, [online], http://dx.doi.org/10.1016/j.isprsjprs.2012.11.006

Ni, Z., et al. (2024) *Parametric Digital Twins for Preserving Historic Buildings: A Case Study at Löfstad Castle in Östergötland* , [online], http://dx.doi.org/10.48550/arXiv.2410.14260

Oxman, R. (2006) 'Theory and design in the first digital age', *Design Studies*, 27(3), pp. 229–265, [online], http://dx.doi.org/10.1016/j.destud.2005.11.002

Republic of Serbia (2018) *Regulation on Detailed Conditions for the Digitization of Cultural Heritage*, "Official Gazette of RS", No. 76/2018, [online], https://www.paragraf.rs/propisi/pravilnik-blizi-uslovi-za-digitalizaciju-kulturnog-nasledja-republika-srbija.html

Remondino, F. and Campana, S. (2014) *3D Modelling in Archaeology and Cultural Heritage—Theory and Best Practices*, [online], Archaeopress Publishing Ltd, https://www.academia.edu/5719952/3D_Modeling_in_Archaeology_and_Cultural_Heritage_Theory_and_Best_Practices

Tryfonos, G., et al. (2021) *Cultural Heritage Monument Documentation Through Adaptive Parametric Design Process*, [online], http://dx.doi.org/10.5194/isprs-archives-XLVI-M-1-2021-769-2021

Volk, R., Stengel, J. and Schultmann, F. (2014) 'Building Information Modeling (BIM) for existing buildings—Literature review and future needs', *Automation in Construction*, 38, pp. 109–127, [online], http://dx.doi.org/10.1016/j.autcon.2013.10.023

3DCP VS CONVENTIONAL CONSTRUCTION. COMPARATIVE ANALYSIS OF ENERGY PERFORMANCE AND EMBODIED CARBON

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ABSTRACT:

3D Construction Printing (3DCP) is an emerging technology that has shifted from the research realm to that of the commercial. This shift can be credited to the various advantages that such approach offers, for instance, increased design freedom, affordability and higher levels of sustainability. Projects originating from *ICON* (de Souza et al, 2024) and *Mario Cucinella Architects* (Gomaa et al, 2022) are representative of this. However, despite the media exposure, detailed and impartial

assessments on the performance of such projects have not yet been rigorously disclosed.

In the past year, the authors of this paper have collaborated with *Havelar*, a 3DCP construction company based in the north of Portugal. After purchasing a large-scale 3D printer from *COBOD*, produced two of the first 3D printed houses in the country. This unique collaboration between academia and industry, has allowed the research to overcome many limitations commonly associated to exclusively academic investigations. Consequently, the research has been confronted with the tangible challenges of full scale 3DCP, such as, design, material, performance and finance issues.

The current paper draws from this privileged experience, by scientifically assessing the ecological impacts of 3DCP and by comparing them to conventional construction techniques (Kyriakidis et al, 2018) within Portugal. The ecological aspects that will be analysed, will be the life cycle assessment (Motalebi et al, 2024) and the energy performance (Sovetova & Kaiser Calautit, 2024). In doing so, the paper proposes and describes a digital workflow to assess the performance of those buildings.

This research can positively impact both the academic and non-academic communities, by providing actual data on 3DCP along with providing a methodology for further projects. Thus, encouraging improvements within the field and subsequently instigating new research directions, that can promote a more sustainable 3DCP strategy.

Keywords: Energy Performance/Life Cycle Assessment/3D Construction Printing/Sustainable Construction/3D Printed Architecture

INTRODUCTION:

3D Construction Printing (3DCP) is a disruptive construction technology that has been incrementally gaining momentum, as the trajectory of the US-based company *ICON* shows (Azevedo, 2025). In Portugal, under the vision of José Maria Ferreira, the company *Havelar* was founded, making it the first 3DCP company in the country in 2023, following the procurement of *COBOD* infrastructure. On the global stage, support for this technology is encouraging the development and exploration of new frontiers, a recent example being Qatar´s design of the *PPP Schools.* This 40,000 square-meter complex is currently utilising one of the largest 3DCP gantry systems in the world, branded as the *BODXL* (Sher, n.d.). This steady support for the technology is substantiated by the panoply of solutions offered to the construction industry. These include transitioning towards a more sustainable, automated, and highly productive sector. Such advancements must be applied and analysed at the local scale to ensure they can be appropriately assessed. After all, each context is composed of a compilation of contextual factors, such as climate, economy, raw materials, construction methodologies, politics and history.

This tailored research approach towards the application of 3DCP has begun to be applied within academic research (Batikha et al., 2022), fostering the possibility for a more in-depth discussion related to the application of such technology. This article continues with this tailored approach, with the investigation centring on Portugal a Western European Member state. It will proceed with a comparison of two non-loadbearing walls, a traditional wall system and a locally printed 3DCP wall. They will be analysed in terms of two locally relevant parameters: thermal performance and life cycle assessment, which will consequently indicate which of the following walls are best suited to the Portuguese context.

METHODOLOGY:

Following a thorough literature review, it became apparent that a wall produced in the 1980s (Rosa, 2009), known as the double hollow core wall (Annex 1), was the most representative construction system in Portugal, as utilised by Monteiro (2017) and Nantes (2022). We shall compare this system with the first 3DCP concrete residential project (Annex 2), produced by *Havelar,* designed by the architecture studio *OODA*, engineered by *LA III,* and assisted by *COBOD*, providing the basis for an accurate analysis.

Upon evaluating the current state of Portuguese housing, it became apparent that two predominant areas need to be resolved: (1) energy poverty and (2) embodied carbon. Energy poverty is deeply ingrained in Portuguese culture, characterized by the population's inability to heat their households in winter (Anon, 2025b) Portugal's energy poverty is ranked among the highest in Europe, placing it in fifth place (Anon, 2025b). The implications of this situation upon society are hugely worrying, with studies associating cold homes with cardiovascular and respiratory diseases (Dear & McMichael, 2011), along with mental health issues (Thomson, Snell & Bouzarovski, 2017a). Notably, these pose a significant risk to the elderly, leading to an increase in mortality rates during the winter (Thomson, Snell & Bouzarovski, 2017b). For a country considered to have one of the oldest populations in the EU (Lopes et al., 2023), this is highly alarming. The relevance of this has been at the forefront of society, therefore encouraging the approval of *"Resolução no11/2024"* Resolution no11/2024 *which* decrees the creation of the *"Estratégia Nacional de Longo Prazo para o Combate a Pobreza Energética (ELPPE)"* National long-term strategy to combat energy poverty (Anon, 2024), which strives to combat it. The construction sector, however, must also adapt to these conditions and develop more high-performance solutions that are both cost-effective and efficient. Our investigation aims to determine which of the systems mentioned above exhibits superior thermal performance.

The second adversary addressed in this article is embodied carbon in construction. In the case of Portugal, the values of the industry are unclear; therefore, it is necessary to refer to the EU, which provides an understanding of the current conditions of its member states. Recent reports indicate that 10 percent of the greenhouse gas emissions are accounted for by the embodied carbon of buildings (Den & Hvid, n.d.). The objective is to reduce this value to reach the EU goal of carbon neutrality by 2050 *(Anon, n.d.a)* and a method of doing this is employing materials more efficiently, with the expectation of reducing Greenhouse House Gas (GHG) emissions by 80% (Anon, n.d.b). Whilst the industry strives to reduce the implications of embodied carbon, it is simultaneously constructing at a vast scale, and this is evident within the Portuguese context. As the construction industry in 2025 is projected to grow between 3-5% (Anon, n.d.b), which consequently implies the GHG of the industry will also rise. Especially as it still predominantly relies on traditional construction systems, with a transition to emerging technologies currently at its cusp. Therefore, an important issue within the construction sector remains, requiring thorough evaluation. This investigation aims to determine which of the following wall types demonstrates reduced embodied carbon, utilising Life Cycle Assessment (LCA) as the analytical framework.

METHOD:

To perform a rigorous comparison between the differing wall systems, it was necessary to impose constants within the experiment. Hence, we stipulated that each wall would be 2.8m tall, a dimension representative of a ground-floor building, and 1m wide, a standard unit of measurement.

Within the following experiment, the variables would be the walls and their depth, which are influenced by the parameters of each system.

As previously mentioned, the investigation is divided into two subcategories: thermal performance and LCA. They will both follow the same workflow, which involves gathering and processing data. The thermal performance will be determined by compiling the technical datasheets of numerous materials, followed by translating the data from total thermal resistance (R-value) to total thermal conductivity (U-value). Below are the equations utilized to calculate the following parameters.

Equation of total thermal resistance:

$$\Sigma R_{thermal} = R_{Exterior} + R^{Interior} + R_{Interior}$$

The U value, also known as thermal conductivity, is inversely proportional to that of the total thermal resistance; therefore, the larger the thermal resistance, the smaller the thermal conductivity.

Equation to calculate the total thermal conductivity:

$$U = 1/\ \Sigma R_{thermal}$$

Following the calculation of the U values for the differing envelopes, it was then possible to examine whether the opaque surfaces fell within the delimitations of the thermal coefficients of vertical elements for continental Portugal, the autonomous region of Madeira, and the Azores. As indicated within *"Portaria138-I/2021"* Ordinance138-I/2021 (Rosa, 2021).

The climate within continental Portugal and its autonomous regions varies; subsequently, there are three categories of winter: I1, I2, I3 (Rosa, 2021). The following categories are organized from least cold to coldest. Consequently, the least cold would allow for a higher thermal coefficient of transmission, and the latter would impose a lower maximum U value. Therefore, assisting architects and engineers when designing the vertical and horizontal surfaces. Following the calculations of the U values for the two opaque walls, we will test them to determine if they meet the parameters of the Portuguese legislation.

The LCA is applied in stages A1-4, which include (A1) raw material supply, (A2) transportation, (A3) manufacturing, and (A4) transportation to the site. The reason for delimiting the investigation to these categories is due to two predominant factors; firstly, there is not enough tangible data to support the analysis of the traditionally constructed wall, and to compare the use stage, B1-B7, it would be necessary to place the wall with the same depth, which would consequently eliminate the purpose of this research, which is not to alter the properties of the wall and therefore maintaining its thickness. The selected site for this experiment will be *Havelar´s* headquarters in *Vilar de Pinheiro*, *Vila do Conde*. We decided upon this, as *Havelar* provided accurate data on the 3DCP wall, providing an ideal starting point for the investigation. On the contrary, the traditional wall was merely a theoretical exercise to analyse, and therefore, we searched for suppliers close to the site, with cost not being a consideration.

The workflow is organized as follows: modelling of walls within *Rhinoceros 3D*, extrapolation of data from it, and conversion to kilograms using the technical data sheets of the materials. These material quantities do not account for material wastage, opting for 100% optimal usage. These are then multiplied by the carbon produced, which is sourced from the *Bath Inventory of Carbon and Energy ICE*(Hammond & Jones, 2011. It is essential to note that the carbon data is gathered from a United Kingdom platform and does not include data from other nations within its figures. Therefore, it is expected that the results contain a degree of error; however, they are strongly indicative of the carbon produced. Regarding the distances, they are selected based on the quickest routes to the site and are not influenced by motorway tariffs.

Equation for carbon produced per material

$$kgCO2 = \text{Weight (kg)} \times \text{Emission Factor } (kgCO_2e/kg)$$

Regarding the transportation of materials, there were many vehicles and fuel options to choose from. However, the focus of the study was on the materials and distance; thus, we decided to use the same type of van, which can transport all the materials, thereby producing an emission factor of 0.793 kg CO2e/tonne-km (Anon, 2023).

Equation of transportation

$$kgCO2e = \text{Weight (Tonne)} \times \text{Distance (Km)} \times \text{Emission Factor } (kgCO_2e/tonne\text{-}km)$$

ENERGY PERFORMANCE:

A double hollow core wall is constituted of eight materials, as depicted in the axonometric (annex 1). Its internal structure is comprised of brick, with insulation provided by XPS and a non-ventilated air gap. The internal and external surfaces are covered in plaster and finished with paint (Figure 1: Double Hollow Core Wall – Composition). The sum of these layers account for a thickness of 0.42 m, which is a substantial amount.

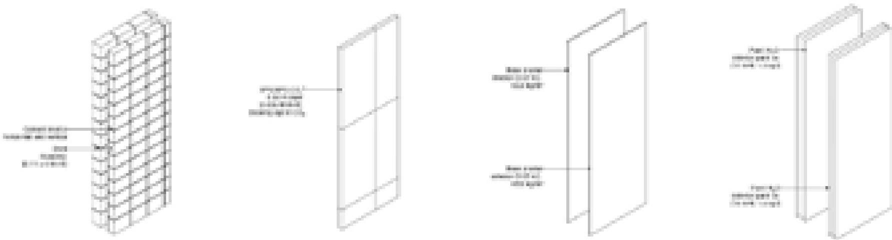

Figure 1. Double Hollow Core Wall - Composition

The numerous layers, along with their thickness, directly increase the thermal resistance of the walls. Consequently, the expectation is that the following wall sample ought to contain a relatively high thermal resistance. To perform a thermal performance analysis, it is necessary to dissect each layer into its states, thereby explicitly calculating the values. In this research, the layers of paint and mortar are not accounted for, as their thermal resistance is deemed ineligible.

Below is the sum of the thermal resistance of the entire traditional wall,

$$\Sigma R_{thermal} = R_{Exterior} + R_{Plaster} + R_{Brick\ 0.11} + R_{Air\ Cavity} + R_{XPS} + R_{Brick\ 0.15} + R_{Plaster} + R_{Interior}$$

$$\Sigma R_{thermal} = 0.04 + 0.02 + 0.297 + 0.110 + 1.714 + 0.429 + 0.02 + 0.13$$

$$\Sigma R_{thermal} = 2.76\ (m2°C)/W$$

As evident in the following calculations, XPS provides a vast amount of thermal resistance, equating to 1.714 $(m^2°C)/W$, followed by the hollow brick at 0.15m, with a thermal resistance of 0.429 $(m^2°C)/W$.

$$U = 1/\ 2.76$$

$$U = 0.36\ W/(m^2°C)$$

Results indicate that the following traditional wall sample, with a thickness of 0.42 m, produces a U-value of 0.36 W/(m^2°C). When comparing these values to the regulation, Ordinance138-I/2021 (Rosa, 2021), the sample fails in the most extreme weather conditions in Portugal, as is evident in Table 2, where the maximum coefficient is stipulated to be 0.35 W/(m2 °C). By increasing the thickness of the insulation used, it would be possible to decrease the U-value of the wall, making it compatible with the stipulated values. However, this would consequently result in a decrease in the cavity, hindering its purpose in both preventing the transfer of moisture and providing acoustic insulation.

Table 1. Double Hollow Core Wall - Composition

Double Hollow Core Wall - U Value 0.36 W/(m2°C)
Maximum surface thermal transmission coefficients of opaque envelope [W/(m2°C)]

	Application	I1	I2	I3
Portugal	Residential	0.50	0.40	0.35
Autonomous Region of Madeira	Residential	0.50	0.40	0.35
Autonomous Region of the Azores	Residential	1.75	1.60	1.45

Note. Data for I1, I2, I3, sourced from *Diário da República* (Rosa, 2021)

3DCP walls are far more optimized in their composition, comprising four materials: digital concrete, rebar, and cork. Due to the wall's structure being composed of a 5cm wide layer, it is possible to reduce the wall's thickness to 0.30m, which can be further reduced. Thus, allowing for a highly competitive construction technique that both architects and engineers would be interested in applying.

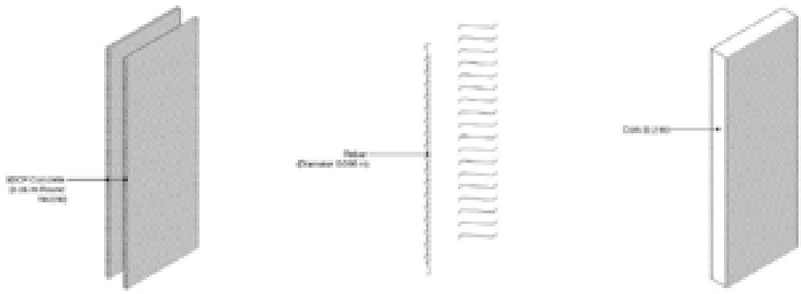

Figure 2. 3D Construction Printed Wall - Composition

For this analysis, the connecting rebar elements will be excluded, as supported by the fact that the rebar has a diameter of 6mm and is concealed within two layers of digital concrete, which would consequently have a minimal impact on the U-value.

The following calculation of the wall is represented below,

$$\Sigma R_{thermal} = R_{Exterior} + R_{Concrete} + R_{Cork\ Insulation} + R_{Concrete} + R_{Interior}$$

$$\Sigma R_{thermal} = 0.04 + 0.021 + 4.878 + 0.021 + 0.13$$

$$\Sigma R_{thermal} = 5.09\ (m^2 °C)/W$$

Note. Data for concrete, sourced from *Havelar (Anon, 2025a)*

As is evident in the calculations, the most influential category affecting the thermal resistance of the wall is cork, which contributes 4.878 $(m^2 °C)/W$. This is in contrast to digital concrete, which contributes 0.042 $(m^2 °C)/W$.

$$U = 1/\ 2.76$$

$$U = 0.20\ W/(m^2 °C)$$

The U value is 1/5.09, which is equivalent to 0.20 $W/(m^2 °C)$. This value is extremely low, especially when considering a thickness of 30 cm, and can outperform the maximum winter requirements (Table 3).

This inferior U-value is achieved due to two-thirds of the wall's thickness being comprised of granulated cork.

Table 2. 3DCP Concrete Wall – Delimitations of the thermal Coefficient of Transmission

3DCP Wall - U Value 0.20 W/(m2°C)				
Maximum surface thermal transmission coefficients of opaque envelope [W/(m2°C)]				
Regions	**Application**	**I1**	**I2**	**I3**
Portugal	Residential	0.50	0.40	0.35
Autonomous Region of Madeira	Residential	0.50	0.40	0.35
Autonomous Region of the Azores	Residential	1.75	1.60	1.45

Note. Data for I1, I2, I3, sourced from *Diário da República* (Rosa, 2021)

Upon evaluating the results of both sample walls, it is evident that 3DCP walls outperform those of the traditional system in terms of both U-values and wall thickness. The traditional wall achieves 0.36 W/(m²°C), compared to the emerging 0.20 W/(m²°C), which aligns with thermal legislation. From an architect's and engineer's perspective, the latter provides a means of reducing the construction area and increasing the usable area, which will be of utmost importance when complying with Portuguese legislation. The possibility of using a lower thermal conductive wall is also highly appealing, as it will improve the thermal comfort of the space while complying with the legislation.

Consequently, it outperforms the requirements stipulated by Portuguese legislation, and its value is accordingly inferior. This means that it could be possible to reduce the thickness of the cork layer to 0.11m, subsequently reducing the wall to 0.21m while still achieving an acceptable U-value of 0.35 W/(m²°C). This assumption excludes the need to place load-bearing structures within the envelope. Otherwise, it would be necessary to increase the cavity to account for the subsequent structure.

LIFE CYCLE ASSESSMENT:

In the following investigation, the traditional wall accounts for an approximate weight of 657.25 kg. This approximate evaluation can be understood by dissecting the wall into three categories: structural, insulation, and finishes. The structure accounts for the predominant weight, 414.37 kg, the insulation accounts for 5.29 kg, and the finishes account for 186.89 kg. The implication of constructing with such a large sum of material is that it will directly increase its embodied carbon for both the production and transportation stages. Consequently, the production stage produces 253.05 kgCO2e; a predominant amount of this value is accounted for within the bricks, at 208.88 kgCO2e.

Table 3. Double Hollow Core Wall – Product Stage *Note.* Data for embodied Carbon kgCO2e/kg, sourced from (Hammond & Jones, 2011)

Double Hollow Core Wall

Category	Material/Product	Weight kg	Embodied Carbon ($kgCO_{2}e/kg$)	Embodied Carbon ($kgCO_{2}e$)
Structure	Brick 0.11	183.12		
	Brick 0.15	231.25	Table 3.1	Table 3.1
	Cement Mortar	50.70		
Insulation	XPS	5.29	3.29	17.40
Finishing	Plaster (Interior)	92.40	0.13	12.01
	Plaster (Exterior)	92.40	0.13	12.01
	Paint (Interior)	1.18	1.31	1.55
	Paint (Exterior)	0.91	1.31	1.19

Table 3.1

Category	Double Skin Walls (m2)	Embodied Carbon ($kgCO_{2}e$ per unit)	Mass per declared unit - (kg)	Embodied Carbon ($kgCO_{2}e$)
Structure	2.8	74.6	m2	208.88

Total Weight (kg)	**657.25**
Embodied Carbon ($kgCO_{2}e$)	**253.06**

Note. Data for embodied Carbon kgCO2e per unit, sourced from (Hammond & Jones, 2011)

Finally, the sum of the embodied carbon within the transportation stage is 25.93 kgCO2e. Upon analysis of the subsequent data, this value is predominantly caused by the transportation of the bricks, as they have a significant value for tonne-kilometre (t.km), which equates to 32636.52, multiplied by the distance travelled of 178 km, sees the production of 25.88 kgC02e.

Table 4. Double Hollow Core Wall – Embodied Carbon produced from Transport

Double Hollow Core Wall

Category	Material/Product	Weight (kg)	Distance (km)	Emission Factor (kgCO2e/t.km)	Tonne-Kilometre (t.km)	Carbon (kgCO2e)
Structure	Brick 0.11	183.12	178.00	0.79	32636.52	25.88076
	Brick 0.15	231.25				
	Cement Mortar	50.70	210.00	0.79	10.65	0.00844
Insulation	XPS	5.29	52.00	0.79	0.28	0.00022
Finishing	Plaster (Interior)	92.40	273.00	0.79	50.45	0.04001
	Plaster (Exterior)	92.40				
	Paint (Interior)	1.18	5.90	0.79	0.01	0.00001
	Paint (Exterior)	0.91				
Total Carbon (kgCO2e)		25.93				

Note. Data for embodied Carbon kgCO2e/kg, sourced from (Anon, 2023)

Before commencing the analysis of the embodied carbon of the emerging wall, it is firstly necessary to clarify that the recipe to be analysed is a mere approximation to the walls printed by *Havelar*. Furthermore, the recipe will not disclose the individual ingredients and instead will refer to the total sum. In this manner, respecting the confidentiality of its material recipe. As evident in the graph below, the entire weight of the wall is approximately 533.8 kg. The concrete mix accounts for 489.6 kg, the rebar accounts for 3.6 kg, and the granulated cork accounts for 40.6 kg.

Table 5. 3DCP Concrete Wall – Product Stage

3DCP Concrete Wall

Category	Material/Product	Weight (kg)	Embodied Carbon (kgCO2e/kg)	Embodied Carbon (kgCO2e)
Structure	Concrete	489.60	3.98	123.00
Reinforcement	Rebar	3.60	1.99	7.16
Insulation	Granulated Cork	40.60	0.19	7.71
Total Weight (kg)		533.80		
Embodied Carbon (kgCO2e)		137.88		

Note. Data for concrete, sourced from *Havelar (Anon, 2025a)*
Note. Data for embodied Carbon kgCO2e/kg, sourced from (Hammond & Jones, 2011)

The implication of having a reduced weight is that the total amount of embodied carbon produced within the production phase is 137.88 kgCO2e. Upon dissecting this data, it is evident that concrete produces most of the CO2, with a total of 123 kgCO2e. The second most influential materials are cork, which makes a total of 7.16 kg CO2e, and rebar, which produces 7.71 kgCO2e. In reality, it is expected that cork would be a negative value and therefore the following figure is not representative of the Portuguese context.

Due to a reduced amount of material being transported to the site, the value of CO2 produced per kilogram is greatly reduced, consequently accounting for 0.048 kgCO2e, which is extremely low. Upon further analysis of the data, it is evident that the concrete recipe is the primary contributor, producing a total of 0.0465 kgCO2e.

Table 6. 3DCP – Embodied Carbon produced from Transport

3DCP Concrete Wall

Category	Material/Product	Weight (kg)	Distance (km)	Emission Factor (kgCO2e/t.km)	Tonne-Kilometre (t.km)	Carbon (kgCO2e)
Structure	Concrete	489.60	X	0.79	X	0.04650
Reinforcement	Rebar	3.60	14.20	0.79	0.05	0.00004
Insulation	Granulated Cork	40.60	40.10	0.79	1.63	0.00129
Total Carbon (kgCO2e)		0.0478				

Note. Data for concrete, sourced from *Havelar (Anon, 2025a)*
Note. Data for embodied Carbon kgCO2e/kg, sourced from (Hammond & Jones, 2011)

Traditional construction systems have a far superior embodied carbon footprint, both in terms of the material and its transportation. This is predominantly because all the materials are bought in product form, where they have already been processed and then need to be assembled on-site. This is completely the opposite for 3DCP, whereby most of the materials are purchased in their minimally processed state and then combined on-site to 3D print. From an engineering perspective, the weight of the wall is also influential when calculating the load-bearing structure, as, in principle, the heavier it is, the more structural elements are required. Therefore, it has implications for the architecture.

CONCLUSION:

The 3DCP wall outperforms that of the double hollow core wall, as it has a reduced thermal conductivity value and a lower embodied carbon value. Furthermore, it achieves this with reduced thickness and weight, providing architectural and engineering benefits, such as increased floor area and reduced load-bearing forces caused by the walls themselves.

Future research should utilize more accurate LCA databases tailored to the Portuguese context, such as *OneClick* LCA, to facilitate a comprehensive analysis. Furthermore, the research produced is merely a benchmark and, therefore, should encourage comparison with other traditional construction systems, with a specific focus on emerging techniques and materials.

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REFERENCES:

Anon (n.d.a) *2050 long-term strategy - European Commission.* https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en [Accessed: 27 June 2025].

Anon (n.d.b) *AICCOPN - Associação dos Industriais da Construção Civil e Obras Públicas.* https://ruis.aiccopn.pt/balanco-de-2024-perspetivas-para-2025/ [Accessed: 27 June 2025].

Anon (2021) *Ambiente e ação climática e infraestruturas e habitação.*

Anon (2025a) *Havelar Materials - Confidential Document.*

Anon (2025b) *Inability to keep home adequately warm.* 16 June 2025. eurostat. https://ec.europa.eu/eurostat/databrowser/view/ILC_MDES01/default/bar?lang=en [Accessed: 26 June 2025].

Anon (2024) *Publicação Estratégia de Longo Prazo de Combate à Pobreza Energética 2023-2050 (ELPPE).* 8 January 2024. Direção-Geral de Energia e Geologia. https://www.dgeg.gov.pt/pt/destaques/publicacao-estrategia-de-longo-prazo-de-combate-a-pobreza-energetica-2023-2050-elppe?utm_source=chatgpt.com [Accessed: 27 June 2025].

Anon (2023) *Van <3.5t - Diesel.* 2023.

Dear, K.B.G. & McMichael, A.J. (2011) The health impacts of cold homes and fuel poverty. *BMJ.* 342 (may11 2), d2807–d2807. doi:10.1136/bmj.d2807.

Den, L. & Hvid, L. (2022) *Aalborg Universitet Towards embodied carbon benchmarks for buildings in Europe Summary report Towards embodied carbon benchmarks for buildings in Europe.* doi:10.5281/zenodo.6397514.

de Souza, E.A. et al. (2024) '3D printed sustainable low-cost materials for construction of affordable social housing in Brazil: Potential, challenges, and research needs', Journal of Building Engineering, 87, p. 108985. doi:10.1016/j.jobe.2024.108985.

Gomaa, M. et al. (2022) 'Digital Manufacturing for Earth Construction: A critical review', Journal of Cleaner Production, 338, p. 130630. doi:10.1016/j.jclepro.2022.130630.

Hammond, G. & Jones, C. (2011) *Inventory of Carbon and Energy (ICE), Version 2.0.*

Kyriakidis, A. et al. (2018) 'Thermal performance and embodied energy of standard and retrofitted wall systems encountered in Southern Europe', Energy, 161, pp. 1016–1027. doi:10.1016/j.energy.2018.07.124.

Lopes, D.G., Mendonça, N., Henriques, A.R., Branco, J., Canhão, H. & Rodrigues, A.M. (2023) Trajectories and determinants of ageing in Portugal: insights from EpiDoC, a nationwide population-based cohort. *BMC Public Health*. 23 (1). doi:10.1186/s12889-023-16370-8.

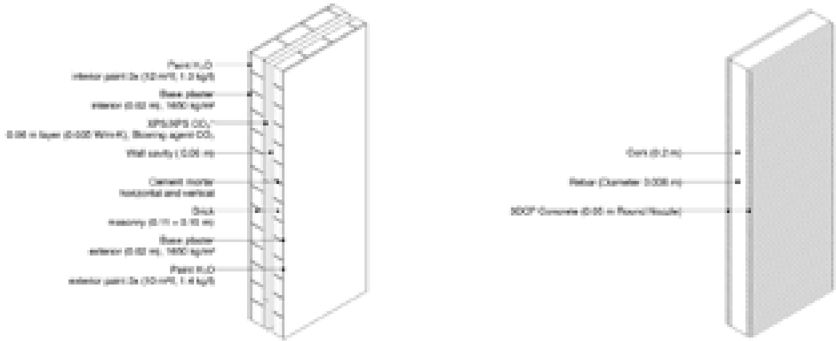
Motalebi, A., Khondoker, M.A. and Kabir, G. (2024) 'A systematic review of life cycle assessments of 3D Concrete Printing', Sustainable Operations and Computers, 5, pp. 41–50. doi:10.1016/j.susoc.2023.08.003

Sovetova, M. and Kaiser Calautit, J. (2024) 'Thermal and energy efficiency in 3D-printed buildings: Review of Geometric Design, materials and Printing Processes', Energy and Buildings, 323, p. 114731. doi:10.1016/j.enbuild.2024.114731.

Thomson, H., Snell, C. & Bouzarovski, S. (2017a) Health, well-being and energy poverty in Europe: A comparative study of 32 European countries. *International Journal of Environmental Research and Public Health*. 14 (6). doi:10.3390/ijerph14060584.

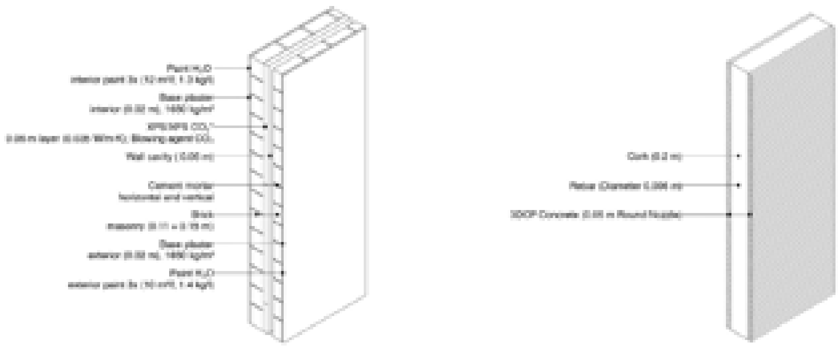
ANNEX:

Annex 1



Double Hollow Core Wall

Annex 2



3DCP Wall

VIRTUAL RECONSTRUCTION OF ARCHITECTURAL HERITAGE: A DIGITAL APPROACH TO PRESERVATION

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ABSTRACT:

Cultural identity and historical integrity face issues such as global underinvestment in architectural heritage preservation, particularly in economically less developed regions where limited funding and technological constraints hinder conservation efforts. Traditional methods often fail to provide long-term protection and accessibility, increasing the risk of losing valuable cultural and historical sites. As digital technologies continue to advance, in response to these challenges, this study explores the integration of 3D modeling, rendering, and Virtual Reality (VR) as an accessible and innovative approach to documenting, preserving, and experiencing architectural heritage.

As part of the Spring School at Bauhaus University in Weimar (March 2024), a five-day workshop was conducted as the final practical

stage of a course that was previously held online. During the online phase, students were introduced to theoretical principles of surveying and documenting historical heritage, gaining essential knowledge of techniques for recording and preserving architectural sites. Building on this foundation, the workshop provided hands-on experience, where participants reconstructed heritage buildings using 3D modeling and rendering software. Once completed, these models were transferred into a VR environment, allowing for immersive interaction with the recreated spaces. This method aimed to bridge the gap between theoretical architectural knowledge and practical engagement, offering new perspectives on spatial awareness, historical context, and design interpretation.

The expected outcomes of this research include improved methodologies for heritage education, increased public awareness of architectural heritage through interactive digital experiences, and the development of a scalable framework for digital preservation. By employing VR as a tool for engagement rather than modeling, this study demonstrates its potential to enhance traditional conservation efforts, making them more interactive, accessible, and cost-effective. The findings advocate for the broader adoption of digital tools in heritage preservation, emphasizing their role in the conservation of historical sites for future generations.

Keywords: Virtual Reality (VR), Architectural Heritage Preservation, 3D Modeling and Rendering, Digital Documentation, Heritage Education

1. INTRODUCTION

Architectural heritage represents the tangible connection to our cultural past, embodying the historical evolution of societies and technological advancements across generations. However, many historic sites worldwide face threats from neglect, conflict, environmental factors, and limited conservation resources. Traditional preservation approaches often struggle with challenges of scale, access, and funding, particularly in economically less developed regions where heritage protection competes with immediate social needs. The documentation and preservation of these irreplaceable cultural assets has become increasingly urgent, requiring innovative solutions that can bridge resource gaps while maintaining scientific consistency.

Digital technologies, especially 3D modeling and Virtual Reality (VR), have emerged as powerful tools in this context. As UNESCO and other international bodies have noted, digital approaches offer non-invasive means to document, interpret, and share cultural heritage on unprecedented scales (Ma et al, 2025). These technologies create permanent digital records of sites that might otherwise deteriorate or be lost entirely, while simultaneously providing interactive platforms for education and public engagement.

This paper examines a pedagogical implementation of digital heritage preservation conducted through a Spring School workshop at Bauhaus University Weimar in March 2024. The project, titled "Virtual Reconstruction of Architectural Heritage: Preserving the Past in the Digital Age," combined theoretical instruction with practical application of digital documentation and VR visualization techniques. International students from diverse backgrounds collaborated to create virtual reconstructions of heritage buildings, culminating in immersive presentations that showcased both technical proficiency and interpretive understanding.

The workshop addressed several key questions at the intersection of heritage conservation and digital technology: How can 3D modeling and VR enhance understanding of architectural heritage beyond traditional documentation methods? What workflows and methodologies are most effective for teaching these techniques to future heritage professionals? And how might such approaches scale to address broader preservation challenges in various global contexts?

By analyzing this educational case study, we aim to contribute to the growing discourse on digital heritage methodologies, particularly regarding their implementation in teaching environments and their potential for expanding access to cultural knowledge. The paper begins with a review of relevant literature, followed by a detailed description of the workshop methodology, analysis of student outcomes, and discussion of broader implications for heritage education and preservation practice.

2. BACKGROUND AND THEORETICAL FRAMEWORK

The digital documentation and visualization of architectural heritage has evolved substantially over the past two decades, progressing from basic 2D digitization to complex interactive 3D enviroments. This evolution has paralleled advances in information and communication technology (ICT), particularly the development of accessible 3D modeling platforms, photogrammetry techniques, and immersive visualization hardware.

2.1 Digital Documentation Approaches

Contemporary high-precision digital documentation encompasses integrated techniques including laser scanning, photogrammetry, structured light scanning, and hybrid approaches that combine multiple data sources to generate detailed 3D data capturing millimeter-level surface details of heritage structures (Tysiac et al, 2023). These technologies generate detailed 3D data that can capture millimeter-level surface details of heritage structures, creating accurate digital surrogates (Ma et al, 2025). Such data serves not only documentation purposes but also provides the foundation for subsequent analysis, monitoring, and virtual reconstruction (Muralidhar et al, 2022).

Modern heritage virtualization relies on a range of advanced 3D acquisition techniques and integration platforms. High-resolution data are commonly captured through close-range photogrammetry (terrestrial and aerial), laser scanning, and mobile mapping systems. These workflows produce detailed 3D point clouds, textured meshes, and 360° panoramas (Maset et al, 2022; Perfetti et al, 2023).

For instance, Maset et al. (2022) combined terrestrial photogrammetry with a portable LiDAR mobile mapping system to model Lebanon's Bziza Temple, demonstrating how multi-sensor methods compensate for the limitations of each individual technology. Similarly, Perfetti et al (2023) utilized a backpack-mounted MMS (Gexcel Heron Lite) together with a UAV (DJI Mini 2) to rapidly survey two historic churches in Brescia, Italy, producing complete point clouds and metric 3D models, later published as an interactive "metric virtual tour" via the Cintoo platform.

These approaches often integrate multiple complementary sensors, such as UAV and terrestrial photogrammetry, terrestrial laser scanning, and SLAM-based mobile LiDAR, which enhance coverage, accuracy, and efficiency (Maset et al, 2022; Perfetti et al, 2023). The resulting geometric and visual datasets form the foundation for immersive applications like 360° virtual tours and textured mesh environments.

Building Information Modeling (BIM) has further extended these capabilities, with Heritage BIM (H-BIM) emerging as a specialized approach for historic structures. As Chen et al, (2023) demonstrate, H-BIM enables "digital restoration of modern architectural heritage" by integrating geometric data with semantic information about materials, construction techniques, and historical context. This integration allows for more comprehensive documentation that extends beyond mere visual appearance to include structural analysis and conservation planning.

2.2 Virtual Reality in Heritage Contexts: Methods and Technologies

While documentation technologies create digital data, VR provides immersive means to experience and interpret this information. Besoain et al, (2021) note that VR offers a qualitatively different engagement with heritage content compared to traditional media, with users experiencing a strong sense of presence and embodied interaction with virtual spaces. This "sense of being there" fundamentally changes how users perceive and learn about architectural heritage.

Once data are captured, heritage projects often integrate 3D models and panoramas into interactive virtual tours. Bastanlar et al (2008) describe one of the earliest examples, a web-based system that combined multi-view stereo reconstructions with panoramic images and GIS overlays. Their interface aligned photo-generated 3D meshes with 360° viewers and excavation site plans, all displayed in a browser. De Fino, Ceppi and Fatiguso, (2020) built on this approach in the EU-funded 3D-IMP-ACT project. They created a WebGIS platform that links photogrammetric 3D models, drone imagery, and spherical panoramas. The resulting portal merges 360° virtual tours with photorealistic models and historical illustrations, allowing users to explore ancient sites through a map-based interface (De Fino, Ceppi and Fatiguso, 2020).

Palamar et al (2024) developed a VR-based virtual museum in Ukraine. They combined Insta360 panoramic images with photogrammetric models of sacred sculptures. Using the Pano2VR platform, they stitched panoramas and embedded clickable 3D object anchors. The final product was a browser-based HTML5 application in which users navigate a museum space and interact with 3D objects directly from within panoramic hotspots (Palamar et al, 2024).

Various software platforms support these experiences.

Real-world projects further demonstrate the practical use of these platforms. For example, the *v-Corfu project* (Komianos, Tsipis and Kontopanagou, 2024) recreated Corfu's Old Municipal Theatre in VR, hosting virtual exhibitions that reached broad audiences, including underserved groups. Similarly, the *Balzi Rossi Virtual Experience* (Iacono, Baldi and Marchesini, 2022) applied photogrammetry and Unreal Engine to immerse visitors in the prehistoric caves of Liguria, integrating multilingual support and temporal reconstruction to enrich public education.

Potree, three.js, and A-Frame are widely used for WebGL-based 3D rendering. Fascia et al (2024) note that these libraries allow tours to run on any browser, which is why they used Potree in their Ricci Oddi Gallery case study to visualize photogrammetry and laser scanning data (Fascia et al, 2024). Garcia et al (2021) built a custom Unity3D viewer for heritage documentation. They used specialized shaders to simulate lighting and exported the results to WebGL for online use (Garcia et al, 2021). Some teams prefer commercial software. The Zbarazh Castle project, for instance, used Insta360 and Pano2VR to combine spherical panoramas and 3D models, placing tour nodes on an interactive layout similar to Google Maps (Palamar et al., 2024). Others, like Perfetti et al (2023), published their church documentation using Cintoo's online platform, making the models accessible on both desktop and mobile devices (Perfetti et al, 2023).

Research has demonstrated several specific advantages of VR for heritage applications.

- Enhanced spatial understanding. Users gain intuitive comprehension of spatial relationships, scale, and proportion that is difficult to convey through 2D media (Besoain et al, 2021).

- Contextual learning. Historical information can be embedded within the environment rather than presented separately, creating situated learning experiences (Ress and Cafaro, 2021).
- Accessibility. Sites that are physically inaccessible due to location, conservation restrictions, or destruction can still be virtually experienced (Tzima et al, 2021).
- Temporal exploration. Multiple historical periods or reconstruction hypotheses can be presented within the same virtual environment (Pietroni and Ferdani, 2021).

Pietroni and Ferdani (2021) emphasize that the value of virtual heritage extends beyond visual replication to encompass interaction and meaning-making: "In the absence of materiality, what emerges as a fundamental value are the interaction processes, the semantic values that can be attributed to the model itself." This perspective frames VR not as a substitute for physical heritage but as a complementary medium with distinct educational and interpretive capacities.

2.3 Educational Value of Virtual Heritage Methods

The integration of digital heritage technologies into educational contexts represents a growing area of interest. Their pedagogical value lies both in the development of technical skills and in fostering conceptual engagement with heritage interpretation. For heritage students, mastering tools for digital documentation and visualization provides crucial competencies in a field that is increasingly technology-driven. At the same time, the process of creating virtual reconstructions requires critical engagement with historical documentation, archaeological evidence, and the interpretive challenges inherent in reconstructing the past—developing what Pietroni and Ferdani (2021) describe as "critical thinking" about heritage.

Educational applications of these technologies typically follow one of two models:

- Technology-focused approaches that emphasize practical skills in using software and hardware tools, and
- Heritage-focused approaches that use digital tools to enhance understanding of historical, cultural, and architectural concepts.

These educational applications are not purely theoretical. In Italy, the *Corsano Castle VR* (De Paolis, Chiarello and De Luca, 2023) project allowed users to explore both architectural features and oral histories, combining tangible and intangible heritage in one immersive experience. This kind of interaction aligns directly with pedagogical goals, as it engages users across sensory and cognitive domains.

The workshop presented and analyzed in this paper aimed to integrate both approaches by embedding technical training within a broader framework of heritage interpretation and conservation principles.

2.4 Digital Heritage Strategies in Economically Challenged Balkan Countries

In many Balkan countries facing economic constraints, digital heritage preservation has emerged as a cost-effective and innovative alternative to traditional restoration, which is often financially unfeasible. Ognjanović et al (2019) emphasize that material heritage in Serbia is at significant risk due to limited funds, a shortage of professionals, and the absence of long-term cultural policy, making digitization a strategic response.

One example is the "Virtual Presentation of the Historical Place Bač" in Serbia, which developed a website, mobile app, and database with 3D models and 360° panoramas of medieval monuments. This initiative demonstrates how digital documentation can enhance heritage accessibility despite budgetary limitations (Ognjanović et al, 2019).

In Bosnia and Herzegovina, Rizvić et al (2021) describe a range of VR and AR projects that preserve both war-damaged and intangible heritage. These include a virtual museum of traditional crafts, a VR documentary on Yugoslav dissidents, and the Sarajevo 5D application, which uses augmented reality to revive destroyed monuments. The VR Sarajevo Tunnel experience allows users to explore life under siege, effectively turning memory into immersive education (Rizvić et al, 2021).

Similar trends can be observed in Greece and Ireland. *Ma et al., 2025* introduced the conceptual model of "digital museums" in Greece, describing how virtual environments extend the spatiotemporal context of cultural heritage. In Ireland, *Meegan et al. (2020)* emphasized how the pandemic accelerated the creation of *Virtual Learning Environments (VLEs)*, providing remote access to heritage content through 3D modeling and interactive tools, particularly for education-focused audiences.

Llabani and Abazaj (2024) documented the Clock Tower in Tirana, Albania, using terrestrial laser scanning. Their work produced a high-precision 3D model used for both conservation and digital tourism. Similarly, Jones and Bevan (2019) applied photogrammetry at the Stobi archaeological site in North Macedonia. Their method improved accuracy from 3 cm to 3 mm and reduced documentation time by 75%, showing the efficiency of digital tools.

In Serbia, Obradović et al (2020) developed a VR model of the iconostasis in the Serbian Orthodox Church of Saint Nicholas using photogrammetry and game engine technology. This allowed users to explore the structure interactively, bridging the gap between physical inaccessibility and digital presence.

Djukić et al. (2019) present the "Digital Mini Museum" project in Niš, Serbia, where students used 3D modeling, QR codes, and simple VR to document and promote local heritage. This low-cost, student-led initiative highlights the potential of educational and community-driven approaches to digital preservation.

A common thread across these projects is that economic limitations often fuel innovation. Technologies like photogrammetry, terrestrial laser scanning, and game-engine VR are shown to be both cost-effective and technically robust (Ma et al, 2025). Supported by academic institutions, NGOs, and occasional government policies, Balkan countries have demonstrated that meaningful heritage documentation is possible even with limited funding.

Serbia's 2019 national cultural heritage strategy, authored by the Ministry of Culture and the Academy of Sciences, offers metadata and digitization standards to help structure and sustain these efforts (Ognjanović et al, 2019).

In summary, digital heritage strategies in the Balkans highlight how constrained budgets can lead to creative, scalable preservation models. From interactive museums to virtual reconstructions, these projects maintain cultural continuity and ensure access to heritage that might otherwise be lost.

2.5 Research Gap

While substantial literature exists on both the technical aspects of digital heritage documentation and the theoretical frameworks for virtual heritage interpretation, fewer studies examine the integration of these approaches in educational settings. In particular, there is limited research on structured pedagogical frameworks that combine heritage theory with hands-on digital practice in workshop formats. This paper addresses this gap by analyzing a specific educational implementation and identifying transferable principles for heritage education.

Before introducing the Spring School case study, it is helpful to situate the project within a broader European context. Across the continent, several initiatives have demonstrated the potential of virtual reality and digital modeling to preserve and communicate architectural heritage.

In Greece, the *v-Corfu* project recreated *the Old Municipal Theatre of Corfu* as a real-time VR environment, offering immersive exhibitions of local monuments. The project achieved high user engagement, including among underserved communities. Similarly, the *Balzi Rossi* project in Italy used photogrammetry and Unreal Engine to reconstruct prehistoric cave sites, enabling visitors to explore different historical periods in a high-fidelity virtual setting.

Another example from Italy is the *Corsano Castle VR* application, which created a low-cost, Oculus-based tour combining 3D scans of the structure with oral histories from local residents. This project preserved both the tangible architecture and intangible cultural memory of a site that is otherwise inaccessible. In parallel, conceptual models for digital museums in Greece have explored how VR can extend the spatial and temporal presence of cultural institutions, allowing users to engage with exhibitions across different contexts.

Ireland's development of Virtual Learning Environments (VLEs) during the COVID-19 pandemic further illustrates how 3D modeling and immersive platforms can ensure continued access to heritage education during periods of physical restriction. These platforms served both students and communities, emphasizing education, accessibility, and remote engagement.

Taken together, these case studies highlight the range of approaches and technologies currently shaping digital heritage practices across Europe. They also reveal recurring themes such as accessibility, immersion, narrative engagement, and cost-effectiveness principles that are directly reflected in the methodology and outcomes of the Spring School workshop discussed below.

3. METHODOLOGY AND RESEARCH

The Spring School workshop titled Virtual Reconstruction of Architectural Heritage employed a mixed-method educational approach. It combined online theoretical instruction with hands-on, in-person training. The structure aimed to build both conceptual understanding of heritage documentation and practical skills using accessible digital tools.

3.1 Course Structure

The workshop was delivered in two phases: an online preparatory phase and an on-site session held in Weimar, Germany. The online phase introduced participants to heritage surveying principles, documentation standards, measured survey techniques and 3D modelling methods used in architectural heritage. Participants also selected sites for reconstruction and began collecting documentation, including archived plans, photographs and historical records, often sourced from city hall archives.

The online sessions were led by Pappal Suneja from Bauhaus University, along with Maja Ilić and Miroslav Malinović from the University of Banja Luka. Their lectures helped establish a consistent methodological foundation, especially important given the international and interdisciplinary backgrounds of the participants.

The on-site workshop was conducted from 14 to 23 March 2024 at Bauhaus University. It was facilitated by Dajana Papaz and Maja Ilić from the University of Banja Luka, together with Pappal Suneja. Each day was structured around specific activities, such as equipment setup, digital modelling, virtual reality testing and presentation development. The emphasis was on using low-cost tools and techniques. Students relied on simple measuring devices, smartphone cameras and freely available software. Rather than depending on expensive 3D scanning technologies, they documented their chosen sites using manual measurements, public records and guidance from local historians.

The outcomes of the workshop, including visual materials and final models, were published on a dedicated website: *www.3dvrheritage--bauhaus-springschool.com* (Figure 1). This platform serves as a public archive of the workshop's results and supports wider engagement with the methods and projects developed.

Fifteen students from eight countries participated: Germany, Spain, Bulgaria, Slovakia, Serbia, the United States, Estonia and Sweden. Disciplines represented included architecture, preservation and digital media. Participants were selected based on their technical proficiency and demonstrated interest in architectural heritage. Team composition was carefully arranged to encourage interdisciplinary collaboration, peer-to-peer learning and the exchange of complementary skill sets.

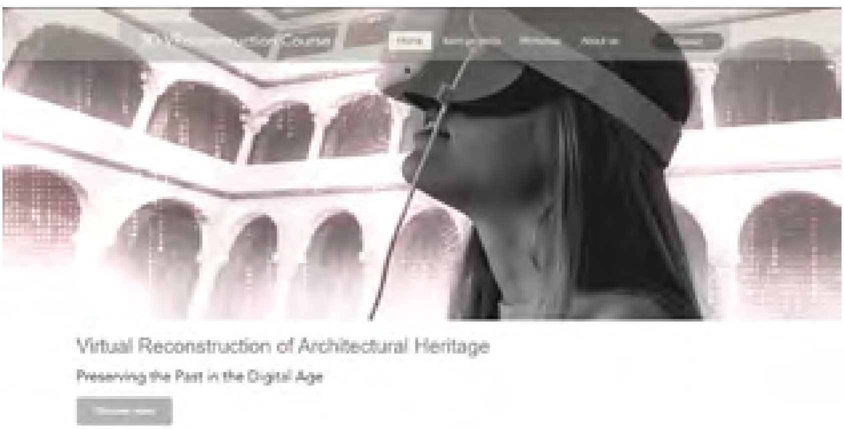

Figure 1: Workshop website showcasing the students' work, workflow, and activities, created by the author.

3.2 Technical Workflow

The workshop followed a structured workflow from documentation to immersive visualization (Figure 2). Teams began by selecting heritage structures and combining historical documentation with new field The practical part of the workshop was divided into two well-defined phases, each designed to lead participants through the process of digitally documenting and reconstructing architectural heritage. The workflow emphasized affordability, resourcefulness, and iterative learning using accessible digital tools and minimal equipment.

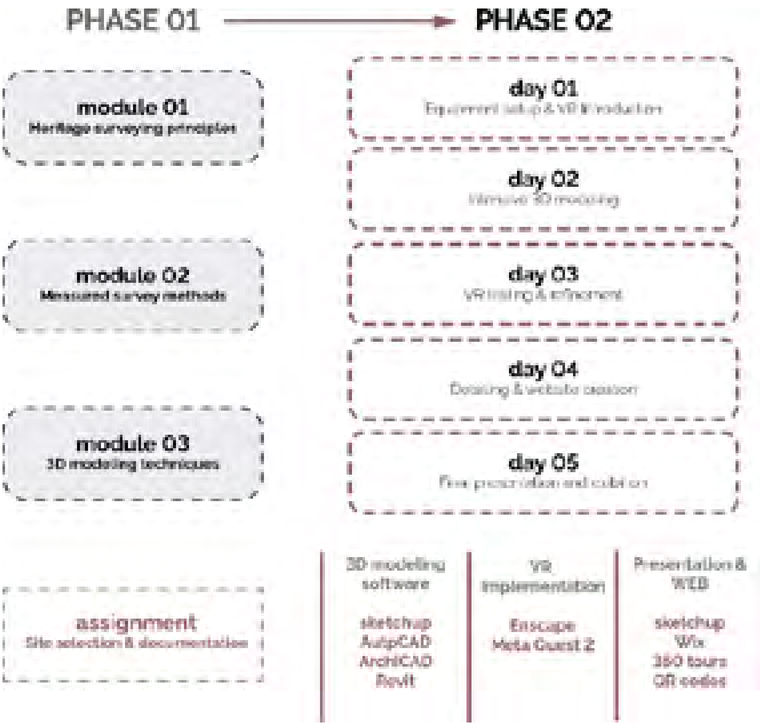

Figure 2: Workflow diagram

Phase 1 focused on foundational knowledge. Through online modules, students were introduced to key topics:

· Module 1: Heritage surveying principles

· Module 2: Measured survey methods

· Module 3: 3D modelling techniques, rendering and website creation

In parallel, students worked on selecting a heritage site from their home country. They began gathering existing resources such as historical photographs, archived documentation, and basic measurements, often using tools available to them like smartphones, measuring tapes, or city hall archives. This pre-workshop phase established a baseline for technical and contextual understanding before the intensive on-site work began.

Phase 2 was held in Weimar (Figure 3) and lasted five days. Each day was dedicated to a specific step in the digital reconstruction process:

· Day 1: Equipment setup and introduction to virtual reality (VR)

· Day 2: Intensive 3D modelling using tools like SketchUp, AutoCAD, Revit, and ArchiCAD

· Day 3: VR testing and refinement of models for immersive experience

· Day 4: Final detailing and website creation

· Day 5: Public presentation of the completed projects

Figure 3: Student working on their projects, Weimar 2023, photo by author

Participants used accessible and commonly available digital tools. Modelling was done using architectural software suited for accuracy and scale tools such as Sketchup, AutoCAD, ArchiCAD and Revit, while Enscape was used for real-time rendering. The models were integrated into VR platforms, particularly Meta Quest 2, where 360° virtual tours and navigation features allowed immersive exploration. Testing models in VR helped students evaluate spatial proportions, orientation, and user experience, which often led to corrections and refinements.

Photogrammetry was applied where feasible to support visual accuracy. Interpretive content was added in the form of text, interactive points, and visual cues to support user navigation and understanding.

To document and share their results, students created websites using Wix, integrating written explanations, visuals, and QR codes linking to additional digital content. These served as public-facing platforms to showcase their work and contribute to broader heritage awareness.

Figure 4: Exibition day, visitors are entering VR space and exploring the students' projects, photo by author

Throughout the process, the workflow encouraged problem--solving with limited means. Students were challenged to achieve professional results without relying on expensive equipment, highlighting the potential of low-cost tools and collaborative effort in virtual heritage reconstruction.

3.3 Data Collection and Analysis

To assess the impact of the workshop, multiple forms of data were collected. Participants completed surveys before and after the workshop, measuring changes in technical knowledge and confidence with digital heritage methods. Each team submitted workflow documentation describing software choices, modelling strategies, and interpretive decisions.

Visual outputs, including 3D models, website content, and immersive VR scenes, were analysed for clarity, usability, and historical coherence. Qualitative feedback was also gathered through informal interviews and post-workshop reflections, which provided insights into the user experience, perceived value of VR, and challenges encountered during the modelling process.

Particular attention was paid to how students addressed incomplete or conflicting documentation, and how they balanced technical limitations with historical accuracy. The analysis highlighted common challenges such as managing uncertainty in historical data and reconciling visual fidelity with software constraints. The immersive VR testing phase was found to be especially effective in revealing spatial issues and encouraging refinement.

4. CASE STUDY: BAUHAUS SPRING SCHOOL WORKSHOP

The application of the described methodology during the Bauhaus Spring School resulted in a diverse collection of virtual heritage reconstructions. These projects serve as case studies, demonstrating how digital tools can be used to document, interpret, and share architectural heritage in a short, intensive educational setting.

Participants chose heritage sites from their home countries, covering a wide range of historical periods and architectural types. Among the selected projects were:

· *Monastery of Yuste (Cuacos de Yuste, Spain):* A 15th-century Hieronymite monastery later expanded in the Renaissance and notable as the final residence of Emperor Charles V. It features two cloisters—Gothic and Renaissance—and the adjoining Palace of Charles V. The student model integrates cloister architecture, ecclesiastical structures, and palace spaces, reflecting its religious and historical importance (Figure 5). *https://deyuste.wixsite.com/monestery-de-yuste*

Figure 5: *Monastery of Yuste (Cuacos de Yuste, Spain),* created by students.

· *King's Railway Station (Sofia region, Bulgaria*): A once-prominent yet neglected railway station restored digitally to its original grandeur. Built in a royal style, it reflects early 20th-century transport heritage and the specific influx of political architecture to Bulgarian rail systems. *https://elementlee.wixsite.com/royalstation*

· *Spanish House (Savamala district, Belgrade, Serbia):* Students dealt with scarce documentation, relying on in situ measurements, archival imagery, and community input to reconstruct this urban heritage building. What made this project special is that they not only digitally reconstructed the building but also proposed repurposing it as a gallery to exhibit all other projects from the workshop (Figure 6). *https://savamala.wixsite.com/spanish-house*

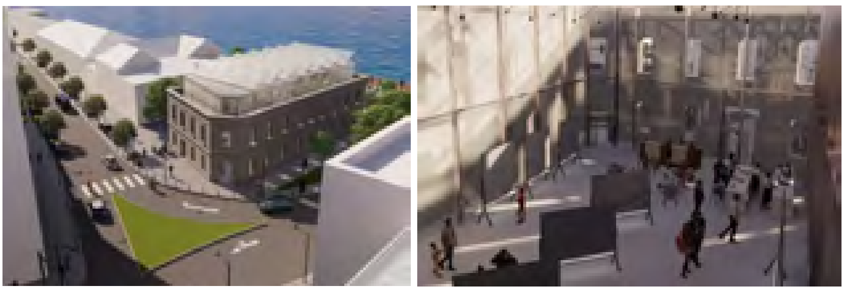

Figure 6: Digital reconstruction of the Spanish House in the Savamala district of Belgrade, Serbia, created by students.

· *Paper Factory (Tallinn, Estonia):* An industrial complex model using layered documentation methods, highlighting production spaces and architectural transitions over time. *https://paperproduction.wixsite.com/factory*

· *St Mary's Chapel (Vychylovka, Bulgaria):* A small vernacular wooden chapel recreated using local oral histories, photographs and measured drawings to preserve a deteriorating rural monument digitally. *https://vychylovka.wixsite.com/preserving-the-past*

The range of cases allowed for comparison of different documentation challenges. Some teams had access to measured drawings and photographic archives, while others relied on hand measurements and anecdotal historical accounts. This variety led to creative problem-solving and highlighted the importance of adaptability in digital heritage practice.

4.1 Documentation, Modelling Process, VR Implementation and Experience

Documentation strategies were selected based on the availability and reliability of source material. Archival drawings, photographs, site measurements, and photogrammetric models were used in varying combinations. In some cases, students accessed city archives or local historians to support their research.

Teams often encountered discrepancies between historical sources and current site conditions. Decisions had to be made regarding the level of detail, treatment of missing features, and representation of uncertain elements. Color coding and layered visualization were used in several models to distinguish reconstructed features from confirmed ones. Modelling involved balancing accuracy with technical feasibility. Some elements were simplified to ensure smooth VR performance, while others were enhanced to highlight architectural detail. The process encouraged critical thinking about what constitutes an acceptable interpretation of incomplete heritage.

The integration of the models into VR platforms was a key milestone. Teams prepared their models for real-time rendering by optimizing geometry and adjusting textures. Navigation systems were designed to support architectural exploration, and annotation points provided historical and architectural context.

Immersive testing significantly impacted the modelling process. Many students reported that they noticed problems in spatial proportion or circulation only after viewing the model in VR. For example, one participant stated: “I had modelled the colonnade based on measurements, but only when experiencing it in VR did I realize the ceiling was too low compared to the column spacing.”

Such feedback informed further revisions and led to improved interpretive outcomes. The use of VR also helped participants consider how heritage spaces were originally experienced, deepening their historical understanding.

The workshop concluded with a public presentation, where each team introduced their project through live VR demonstrations. Presentations included:

· A short history of the selected site.

· An explanation of documentation sources and modelling methods.

· A guided virtual walkthrough.

· A discussion of interpretive decisions and visual storytelling.

In addition to live sessions, each group produced a dedicated project website featuring images, embedded videos, and text-based narratives. These sites serve as open-access educational resources, enabling the public and future students to explore the workshop outcomes and learn from the documented processes (Figure 7).

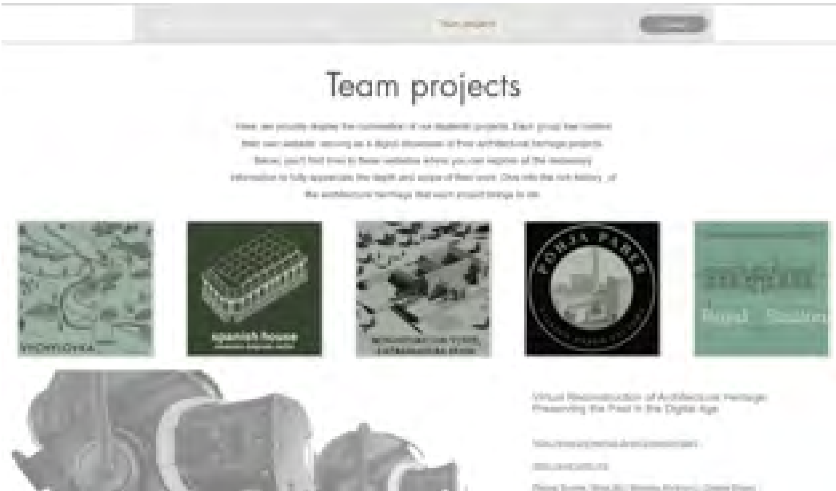

Figure 7: Webpage featuring links and icons for each group's project, created by the author.

5. RESULTS AND ANALYSIS

The Spring School workshop produced valuable outcomes across technical execution, heritage interpretation, educational impact, and practical scalability. These were assessed through documentation, participant feedback, and the immersive reconstructions developed by the teams.

In terms of *technical implementation*, all teams successfully created navigable VR environments using Meta Quest 2 headsets and accessible modelling tools. Model complexity varied: some reconstructions were simplified to ensure smooth performance, while others incorporated rich textures, annotations, and spatial narratives. Notable accomplishments included integrating photogrammetric textures with hand-built geometry, producing visual comparisons between time periods, and designing annotated cutaway models to reveal structural techniques. While students encountered challenges such as texture optimization, managing scale, and embedding interactivity, the iterative cycle of modelling, VR testing, and refinement enabled them to improve both accuracy and user experience.

Heritage interpretation emerged as a key differentiator across projects. Some teams prioritized architectural fidelity, carefully reconstructing material details and spatial layouts; others emphasized experiential aspects such as atmosphere and narrative engagement. A few reconstructions incorporated hypothetical or incomplete elements, particularly where documentation was scarce. Following recommendations by Pietroni and Ferdani (2021), the most methodologically transparent projects clearly distinguished between verified and speculative features using visual cues or annotations, helping to prevent misleading representations.

With regard to *learning outcomes*, participants demonstrated significant gains in digital heritage competencies. They reported increased confidence in using modelling software and VR tools, improved understanding of architectural documentation standards, and enhanced critical thinking about the relationship between physical structures and their digital interpretations. The immersive nature of the VR environment proved particularly valuable: being able to inhabit their reconstructions allowed participants to evaluate proportions, spatial coherence, and historical plausibility more intuitively than on a 2D screen.

The scalability and accessibility of the workshop methodology were also evident. The exclusive use of affordable consumer-grade VR equipment, along with widely available modelling software, allowed students to work without advanced hardware. Field documentation relied on low-cost tools: handheld measuring tapes, smartphone photos, and publicly accessible archives. However, projects with access to detailed historical records or measured drawings (often through city archives or academic libraries) achieved higher levels of historical accuracy. While the five-day on-site format was sufficient for producing a functioning VR experience, some students noted that extended time for research and modelling would allow for deeper engagement and refinement. Basic prior experience with 3D modelling proved essential; complete beginners would likely require preparatory instruction.

6. DISCUSSION

The workshop demonstrated the value of combining physical documentation with virtual representation in heritage education. Participants grounded their reconstructions in physical evidence, working from measurements, photographs, and historical documents. The resulting models provided new ways to understand and interpret architectural space. This supports the idea advanced by Pietroni and Ferdani that real and virtual heritage should be seen as a continuum, where digital tools extend the ability to engage critically with the past. The integration of multiple sources and careful modelling helped ensure that reconstructions were not purely imaginative but anchored in documented history.

Experiencing the reconstructions in virtual reality had a profound educational effect. Several students reported that seeing their models at full scale helped them detect errors in scale and proportion that were not obvious in the modelling interface. This aligns with the work of Ress and Cafaro, who argue that immersive interpretation places the viewer inside the historical narrative and enhances both understanding and emotional connection. The shared experience of moving through virtual spaces also encouraged discussion and collaboration, which further reinforced the educational value of the exercise.

Methodologically, the workshop offers a replicable model for digital heritage education. Key elements included iterative testing and refinement, interdisciplinary teamwork, process documentation, and public dissemination. Students not only built models but also reflected critically on their sources, decisions, and interpretive choices. The inclusion of web platforms and public presentations ensured that the projects extended beyond the academic setting and could contribute to wider heritage awareness.

Participant evaluations further reinforced the effectiveness of this approach. All twelve respondents expressed overall satisfaction with the workshop and stated they would recommend it to others. Many emphasized the practical value of developing skills in 3D modelling and immersive visualization using accessible, low-cost tools. The diversity of the participant group was seen as a major strength, with students highlighting the interdisciplinary and intercultural exchange as essential to the collaborative dynamic. The on-site component in Weimar was especially well received, with students appreciating the guided excursions, hands-on teamwork, and tangible connection to architectural history. At the same time, participants offered constructive suggestions. Several recommended clearer communication and earlier delivery of pre-workshop tasks. Others felt that more time and structure devoted to heritage interpretation would help maintain balance between digital technique and cultural understanding. These comments suggest that while the overall structure is strong, refinements in preparatory guidance and interpretive framing could enhance future iterations.

As demonstrated in other European projects, such as v-Corfu, Balzi Rossi, and Corsano Castle, VR reconstructions can significantly enhance public engagement and educational value. The Spring School workshop builds upon these principles by emphasizing accessibility, low-cost workflows, and interdisciplinary collaboration, particularly in an educational context.

Despite these successes, several limitations were noted. Balancing historical detail with technical feasibility was a constant challenge. Some teams had to reduce model complexity to ensure compatibility with virtual reality platforms. Not all projects clearly marked which parts of their reconstructions were based on conjecture, which risks creating misleading impressions. While the use of immersive virtual reality was highly effective as a learning tool, its long-term accessibility depends on hardware availability and ongoing technical support. Questions also remain about the sustainability of digital outputs, particularly as platforms and software evolve.

Future developments could include closer integration between digital reconstructions and heritage site management, where immersive models inform planning and conservation. Participatory approaches could involve local communities more directly in the documentation and interpretation process. Dissemination strategies should aim to include both immersive and web-based formats to maximize public engagement. Long-term tracking of participants' use of digital heritage skills in professional contexts would offer valuable insights into the educational impact of such workshops. Finally, establishing shared ethical and methodological standards for virtual reconstruction would strengthen the field and support broader collaboration.

7. CONCLUSION

This study has presented an educational workshop focused on the virtual reconstruction of architectural heritage, illustrating how 3D modelling and virtual reality (VR) can be meaningfully integrated into both heritage preservation and pedagogical practice. By combining theoretical foundations with hands-on application, participants developed skills in surveying, digital modelling, and immersive visualization, following a coherent workflow. The case study confirms that immersive reconstruction not only aids in documenting and preserving endangered sites, but also fosters deeper spatial understanding and public engagement. Students moved beyond static representations to experience heritage structures dynamically, aligning with broader scholarship that identifies interactivity and immersion as central values of digital heritage.

The workshop demonstrated that digital approaches offer multiple advantages for heritage education. Immersive environments facilitated intuitive understanding of architectural scale and proportion, while the iterative cycle of modelling and testing promoted critical engagement with historical evidence. The technical nature of the tasks encouraged interdisciplinary teamwork, drawing together heritage expertise and digital proficiency. Importantly, the digital outputs extended public accessibility, enabling heritage content to reach broader audiences through virtual exhibitions and online platforms. The modelling process itself contributed to documentation preservation by generating accurate and detailed digital records of historical structures.

These outcomes suggest that digital tools should be more systematically integrated into heritage education and professional practice. They should not replace traditional methods but serve as complementary instruments that expand interpretive possibilities and long-term preservation capacity. Based on the findings, this study recommends embedding digital heritage techniques within preservation and architecture curricula, fostering interdisciplinary collaboration between heritage professionals and technology specialists, and establishing clearer standards for transparency in virtual reconstructions. Additionally, developing accessible dissemination platforms and dedicated repositories for the long-term storage of digital heritage assets would enhance the sustainability of these efforts.

Although digital technologies cannot substitute the embodied experience of visiting a heritage site, they provide meaningful alternatives that expand access, stimulate learning, and safeguard historical knowledge. As demonstrated in this workshop, the integration of rigorous documentation with immersive visualization creates powerful educational experiences that engage participants with architectural heritage while cultivating essential skills for its ongoing preservation.

8. REFERENCES

Bastanlar, Y., Grammalidis, N. and Zabulis, X. (2008) "3D reconstruction for a cultural heritage virtual tour system," The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVII, Part B5, pp. 1023–1028, Beijing.

Besoain, F., Jego, L. and Gallardo, I. (2021) "Developing a virtual museum: Experience from the design and creation process," Information, Vol. 12, 244, Basel.

Chen, Y., Wang, W. and Sun, C. (2023) "Digital documentation and conservation of architectural heritage using H-BIM and immersive technologies," Journal of Cultural Heritage and Digital Design, Vol. 5, No. 2, pp. 112–128, Beijing.

De Fino, M., Ceppi, C. and Fatiguso, F. (2020) "Virtual tours and informational models for improving territorial attractiveness and the smart management of architectural heritage: The 3D-IMP-ACT project," International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLIV-M-1-2020, pp. 473–480, Valencia.

De Paolis, L.T., Chiarello, S. and De Luca, V. (2022) "Virtual reality for the enhancement of cultural tangible and intangible heritage: The case study of the Castle of Corsano," Digital Applications in Archaeology and Cultural Heritage, Vol. 27, e00238, Amsterdam.

Djukić, A., Antonić, B., Stanković, R. and Tatić, D. (2019) "Digital Mini-museum as an innovative and affordable presentation of local heritage for tourists: Example from Serbia," Proceedings of the 3rd International Conference on Tourism and Business (ICTB 2019), pp. 1–11 Bangkok, Thailand.

Fascia, R., Barbieri, F., Gaspari, F., Ioli, F. and Pinto, L. (2024) "From 3D survey to digital reality of a complex architecture: A digital workflow for cultural heritage promotion," International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLVIII-2-W4-2024, pp. 205–212, Lausanne.

Garcia, T., Lyu, Z. and Tetzlaff, M. (2022) "An online model viewer for cultural heritage in Unity 3D," Archiving 2022 Final Program and Proceedings, Society for Imaging Science and Technology, pp. 50–55, Springfield, VA.

Iacono, S., Baldi, G. and Marchesini, M. (2022) "Virtual reality in cultural heritage: A setup for Balzi Rossi Museum," Applied Sciences, Vol. 14, No. 9, Article 3562, Basel

Jones, K. and Bevan, G. (2019) "A photogrammetric workflow for rapid site documentation at Stobi, Republic of North Macedonia," International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLII-2/W11, pp. 631–638, Milan.

Komianos, V., Tsipis, A. and Kontopanagou, K. (2024) "Introducing digitized cultural heritage to wider audiences by employing virtual and augmented reality experiences: The case of the v-Corfu Project," Technologies, Vol. 12, No. 10, Article 196, Basel.

Llabani, A. and Abazaj, F. (2024) "3D documentation of cultural heritage using terrestrial laser scanning," Journal of Applied Engineering Science, Vol. 22, No. 2, pp. 267–271, Tirana.

Ma, Y., Tong, Q., He, X. and Su, B. (2025) "Exploring virtual restoration of architectural heritage through a systematic review," npj Heritage Science, Vol. 13, Article 167, London.

Maset, E., Valente, R. and Iamoni, M. (2022) "Integration of photogrammetry and portable mobile mapping technology for 3D modeling of cultural heritage sites: The case study of the Bziza Temple," International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLIII-B2-2022, pp. 831–837, Nice.

Obradović, M., Vasiljević, I. and Đurić, I. (2020) “Virtual reality models based on photogrammetric surveys: A case study of the iconostasis of the Serbian Orthodox Cathedral Church of Saint Nicholas in Sremski Karlovci (Serbia),” Applied Sciences, Vol. 10, No. 8, 2743, Basel.

Ognjanović, Z., Marinković, B., Šegan-Radonjić, M. and Masliković, D. (2019) Cultural heritage digitization in Serbia: Standards, policies, and case studies, Sustainability, 11, 4378. MDPI, Basel.

Palamar, A., Voloskyi, V., Kramar, O., Kramar, T., Stankevych, O. and Yatsyshyn, V. (2024) “Information computer system with a virtual tour for cultural heritage preservation of the Zbarazh Castle Museum’s exhibition hall,” CEUR Workshop Proceedings, 3rd International Workshop on Social Communication and Information Activity in Digital Humanities (SCIA-2024), Lviv, Ukraine, 31 October 2024, Lviv.

Perfetti, L., Vassena, G.P.M. and Fassi, F. (2023) “Preliminary survey of historic buildings with wearable mobile mapping systems and UAV photogrammetry,” International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLVIII-M-2-2023, pp. 1217–1223, Florence.

Pietroni, E. and Ferdani, D. (2021) “Virtual restoration and virtual reconstruction in cultural heritage: Terminology, methodologies, visual representation techniques and cognitive models,” Information, Vol. 12, No. 4, Article 167, Basel.

Ress, S.A. and Cafaro, F. (2021) “I Want to Experience the Past”: Lessons from a Visitor Survey on How Immersive Technologies Can Support Historic Interpretation, Information, Vol. 12, No. 15, Basel.

Rizvić, S., Bošković, D., Okanović, V., Ivković Kihić, I., Prazina, I., and Mijatović, B. (2021) “Time travel to the past of Bosnia and Herzegovina through virtual and augmented reality,” Applied Sciences, Vol. 11, 3711, Basel.

Tysiac, P., Sieńska, A., Tarnowska, M., Kedziorski, P. and Jagoda, M. (2023) “Combination of terrestrial laser scanning and UAV photogrammetry for 3D modelling and degradation assessment of heritage building based on a lighting analysis: case study—St. Adalbert Church in Gdansk, Poland," Heritage Science, Vol. 11, Article 53, London.

PARAMETRIC OPTIMIZATION OF THERMAL COMFORT FROM ARCHITECTURAL DESIGN PHASE

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ABSTRACT:

Optimizing thermal comfort in buildings is an increasing priority to address occupant well-being while contributing to sustainability and reducing energy consumption (Alsharif et al. 2021; Rane et al. 2023). Several approaches to thermal comfort have been explored, including optimizing envelope design (Bojic et al. 2013), model predictive control (MPC) for HVAC systems (Carli et al. 10/6/2019), data-driven approaches using machine learning models (Chen et al. 06182021), and statistical methods to integrate thermal comfort into the design of low-energy buildings (Hawila and Merabtine 2021). However, persistent challenges remain major concerns for building professionals. These challenges relate to data transfer, which refers to interoperability between software, data management throughout the building's lifecycle, and time lost during the project development phase. This article explores an approach to optimizing the thermal performance of building using Dynamo integrated into the BIM software Autodesk Revit and the EN15251 standard (now included in

EN16798-1) as a guideline which provides reference parameters for assessing indoor environmental quality. The proposed optimization approach aims to minimize deviations from the comfort temperature and annual thermal loads according to the scenarios. In order to achieve the desired results, we have divided our research into three main stages: firstly, collecting the necessary input data to assess the indoor environmental quality of the building; secondly, modelling the architectural design using the BIM software Autodesk Revit and performing simulations to optimize thermal comfort using Dynamo integrated with Revit; and finally, validating the optimized model by verifying the results according to the standard. The results demonstrate the effectiveness of using Dynamo integrated with Revit to automate analysis, simulation, and optimization cycles from a high-performance design perspective. This approach allows the building to be optimized according to the desired category of thermal conditions while significantly saving considerable time.

Keywords: Thermal Comfort, Thermal Optimization, Comfort Optimization

1. INTRODUCTION

The quest for a comfortable and energy-efficient indoor environment has become one of the strategic priorities in the building sector over the last few decades. According to (UN Environment NaN), the building sector accounts for approximately 37% of global energy consumption and more than one-third of greenhouse gas emissions, placing it at the core of energy transition policies. Consequently, thermal comfort is no longer regarded solely as a subjective well-being factor but also as a determining parameter to be considered for ensuring occupants' health, productivity

(Wargocki 2019), and the overall energy performance of the building (Hawila and Merabtine 2021).

To provide solutions to this major issue, researchers and practitioners have multiplied their approaches to integrate thermal comfort optimization from the design phase. Among these approaches, we note the importance of bioclimatic design and building envelope optimization (Bojic et al. 2013), the use of model predictive controls (MPC) for HVAC systems (Bianchini et al. 2019), the adoption of artificial intelligence and machine learning methods to model thermal behavior (Sibyan et al. 2022), and statistical approaches that better integrate comfort conditions into low-energy buildings (Hawila and Merabtine 2021).

Simultaneously, thanks to the development of the tech industry, the digital transformation of the construction sector has seen a significant boom, notably due to the emergence of Building Information Modeling (BIM) and visual programming tools such as Dynamo, enabling more agile, iterative, and data-driven parametric design processes (Eastman 2011). However, despite this notable progress, several obstacles remain, such as software interoperability, fragmented data management throughout the building lifecycle, and time and cost losses during the project development phase (Kamel and Memari 2019).

This study fits within that context by proposing a method for optimizing thermal comfort using Revit, coupled with Dynamo and Python. The approach relies on the European standard EN15251 (now integrated into EN16798-1), which provides quantitative criteria for evaluating indoor environmental quality. It aims to minimize both deviations from comfort temperature and annual thermal loads. The developed methodology unfolds in three main stages: input data collection, architectural modeling and calculation of optimized parameters, application to the architectural model, and comparative analysis of calculated and simulated performances.

2. LITERATURE REVIEW

2.1. Data required for thermal comfort assessment in buildings

Assessing thermal comfort in buildings relies on analyzing several data types, grouped into three major categories: environmental parameters, occupant characteristics, and building properties. The most essential environmental variables are air temperature, mean radiant temperature, air velocity, and relative humidity, which directly influence occupants' thermal perception (2017; ASHRAE 2017; Fanger 1970; ASHRAE 2017). These data are used to calculate indices such as PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied).

Moreover, occupants' physiological and behavioral characteristics play a major role in evaluating thermal comfort. Metabolic activity and clothing insulation levels determine how a person perceives the thermal environment (Fanger 1970; Schweiker et al. 2020).

Finally, the physical characteristics of the building and its systems also impact the regulation of thermal comfort. This refers to the thermal properties of the envelope (conductivity, thermal capacity, inertia), orientation, solar gains, HVAC equipment (heating, ventilation, air conditioning), and automated or manual control strategies (Bojic et al. 2013; Carli et al. 2019). Today, BIM tools facilitate access to data that centralize geometric, material, and functional information about a building throughout its lifecycle (Eastman 2011; Kamel and Memari 2019).

2.2. Summary principle for material selection based on PMV and orientation

To achieve optimal thermal comfort that meet a PMV (Predicted Mean Vote) as close to zero as possible material selection relies on understanding the interaction between materials and the six thermal comfort parameters defined by Fanger and standardized by ISO 7730.

The general principle involves selecting materials that stabilize air temperature (ta) and mean radiant temperature (tr) at levels compatible with thermal neutrality. This implies using high-performance insulating materials such as wood wool, cellulose wadding, or wood fiber panels to limit thermal exchanges with the outside and maintain indoor stability (Patry et al. 2015). These materials are particularly effective in cold or windy areas (notably for north-facing rooms).

Meanwhile, materials with high thermal inertia such as raw earth, solid bricks, or concrete are crucial, as they can store heat during warm periods and release it when temperatures drop, mitigating radiant temperature variations and maintaining comfort (Fanger 1970). In sun-exposed areas (south and west), this inertia helps limit overheating. In the east, where the sun causes a rapid rise in temperature early in the morning, materials with high thermal lag like cellulose wadding are recommended to delay the impact of solar radiation.

To regulate relative humidity (RH), which indirectly influences thermal sensation, hygroscopic materials such as lime or clay plasters are used. These materials buffer air humidity, improving perceived comfort without the need for mechanical systems (Houssam Affan 2024).

Solar radiation, particularly influential on radiant temperature, can be regulated through the choice of low-emissivity glazing and adjustable solar protections (orientable louvers, exterior shutters), helping to control direct thermal gains while maintaining natural lighting. This is essential to avoid high PMV in south- and west-facing rooms during summer (Hauglustaine et al. 2018).

Natural ventilation helps regulate air speed (va), which is essential for removing excess heat and adjusting comfort, achieved via cross-ventilation designs and the use of air-permeable materials (to some extent).

Thus, to achieve a PMV close to zero, a combination of materials and passive strategies tailored to room orientation, local climate, and human use in line with bioclimatic principles is essential (Fanger 1970). This approach allows for natural and sustainable regulation of indoor thermal comfort, minimizing costs related to active heating and cooling systems.

3. METHODOLOGY

The objective of this research is to develop an approach to evaluate and optimize thermal comfort in the rooms of an architectural model from the design phase using a parametric optimization method.

The expected results aim to guide designers by providing them with a process that automates the evaluation of thermal comfort in the architectural model's rooms, thus enabling architects to rapidly test different design options during the early design phase.

The research methodology relies on using Dynamo scripts coupled with Python in the BIM software Revit, simultaneously addressing data management issues and time losses. The principle is based on three main phases: data extraction, optimization through thermal comfort calculation, and application of the optimized parameters to the architectural model.

Once the architectural model is designed, the optimization process begins with the definition of various thermal comfort calculation parameters: air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, and metabolic activity. Once these shared parameters are created in Revit, value intervals are set for metabolic activity and clothing insulation, as these vary depending on room use and occupants.

The first Dynamo script is then used to extract necessary data for each room and calculate (for a given value within the fixed intervals) the optimal values of thermal comfort parameters radiant temperature, air temperature, air velocity, relative humidity, and PMV using the Dynamo–Python pair.

After determining these parameters, a second Dynamo script is developed to determine the orientation angle of each room relative to the project's geographic north. This is useful for ensuring the desired radiant temperature, selecting appropriate materials, window sizing, and ventilation systems. A verification analysis is then conducted using the EnergyPlus program within the DesignBuilder software.

4. RESEARCH ACTIVITIES

Our research activity begins with the design of an apartment building, which serves as the basis for our studies.

The optimization approach presented in our research is applied to an apartment building consisting of five floors, with each floor containing two apartments, each with two main rooms and a bathroom as shown on Figure1.

Figure 1: Architectural Model

Once the architectural model is created, we proceed with the creation of shared parameters in our model. The shared parameters created are:

- Air speed: related to air velocity in the room, influencing sweat evaporation and thus thermal regulation.
- Air Temp: related to room air temperature, directly affecting the sensation of warmth or cold.
- Clothing Insulation: related to clothing insulation, as clothing affects how the body retains or loses heat.
- Human Activity: related to the level of metabolic activity; the more active a person is, the more heat they generate.
- Radiant Temp: related to the average temperature of surfaces surrounding a person (walls, ceiling, floor, windows).
- Relative Humidy: related to the humidity level in the room.

4.1. Creation of the Dynamo Scripts

To evaluate thermal comfort in the rooms of our architectural model, two Dynamo scripts were created. The first extracts the required data for each room and calculates, using Dynamo and Python, the optimal values of thermal comfort parameters. It extracts clothing insulation and metabolic activity values set by the architect within a defined range, allowing value variation based on room use. Once data is extracted, the script calculates the optimized values of radiant temperature, air temperature, air velocity, and relative humidity for a PMV between –0.5 and 0.5 by testing combinations to find the best-optimized parameters. The script Figure 2 combines the four variables to calculate a near-zero PMV using Fanger's model.

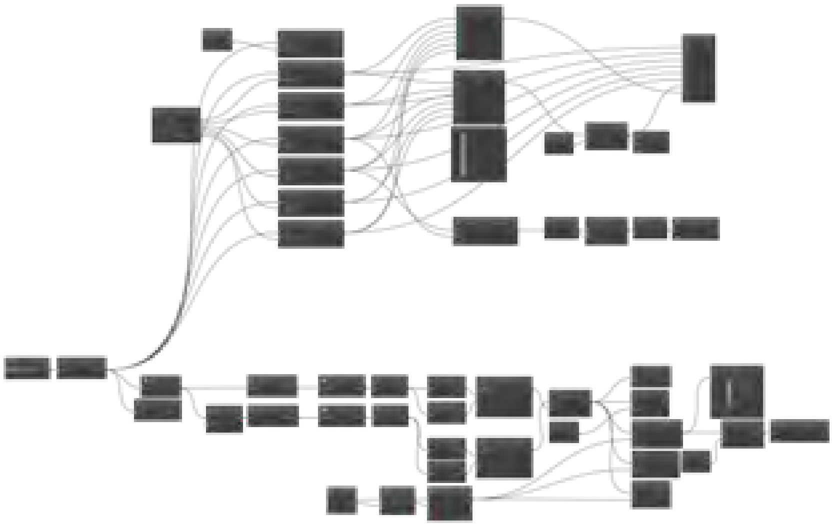

Figure 2: Dynamo script that calculate optimized values to achieve a target PMV

The second Dynamo script Figure 3 is used to determine the orientation of each room relative to the project's geographic north by calculating the angle between the north vector and the vector from the room's center to the window. Positive (trigonometric) and negative directions are interpreted in the script to determine each room's orientation.

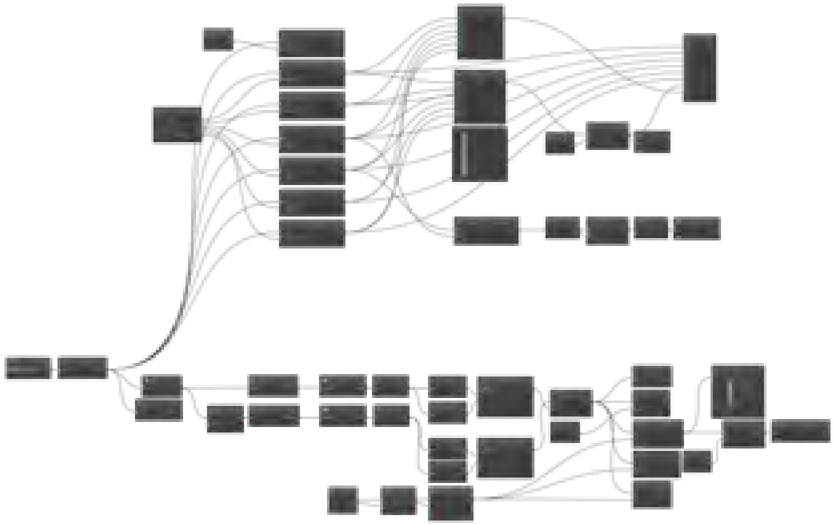

Figure 3: Dynamo script to determine the orientation of each room relative to the project's geographic north

4.2. Results

After creating the 3D architectural model and the shared parameters (Air speed, Air Temp, Clothing Insulation, Human activity, Radiant Temp, Relative Humidy), values for Clothing Insulation and Human Activity are set according to each room's use and function. Data is organized as shown in the table 1 and the first analysis on before optimization was conducted through EnergyPlus and the results in shown on Figure 4.

Table 1: Organization of parameters for three different rooms

Rooms	Parameters	Initial values / To be calculated	PMV
Living room	Air speed	To be calculated	To be calculated
	Air Temp	To be calculated	
	Clothing Insulation	0.85	
	Human activity	1.4	
	Radiant Temp	To be calculated	
	Relative Humidy	To be calculated	
Bedroom	Air speed	To be calculated	To be calculated
	Air Temp	To be calculated	
	Clothing Insulation	0.7	
	Human activity	1.0	
	Radiant Temp	To be calculated	
	Relative Humidy	To be calculated	
Bathroom	Air speed	To be calculated	To be calculated
	Air Temp	To be calculated	
	Clothing Insulation	0.7	
	Human activity	0.8	
	Radiant Temp	To be calculated	
	Relative Humidy	To be calculated	

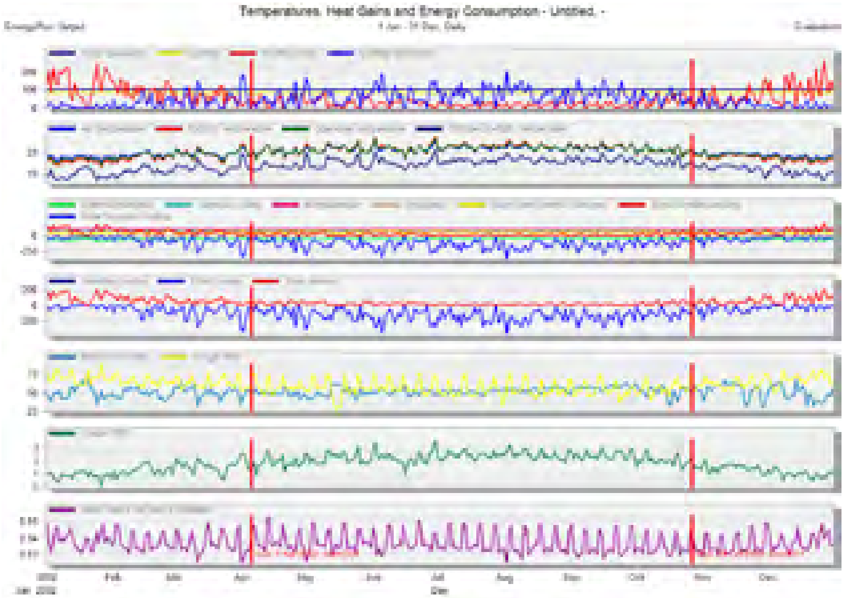

Figure 4: Thermal comfort evaluation results before optimization

Once the data is organized the first Dynamo script is executed to calculate optimized values for Air speed, Air Temp, Radiant Temp, and Relative Humidy, and the results are presented as in table 2.

Table 2: Optimized parameters to achieve target PMV

Rooms	Parameters	Initial values / To be calculated	PMV
Living room	Air speed	0.05	- 0.256
	Air Temp	20	
	Clothing Insulation	0.85	
	Human activity	1.4	
	Radiant Temp	20	
	Relative Humidy	30	

Bedroom	Air speed	0.05	- 0.479
	Air Temp	21	
	Clothing Insulation	0.7	
	Human activity	1.0	
	Radiant Temp	26	
	Relative Humidy	60	
Bathroom	Air speed	0.05	- 0.477
	Air Temp	26	
	Clothing Insulation	0.7	
	Human activity	0.8	
	Radiant Temp	26	
	Relative Humidy	55	

After determining the optimal values to achieve the target PMV, we proceed to determine each room's geographic orientation, which is essential for material selection. After executing the script, we obtain the following results shown in Table 3.

Table 3: Optimized parameters to achieve target PMV

Rooms	Parameters	Initial values / To be calculated
Living room	-5.09	North
Bedroom	90	West
Bathroom	100.2	West

After determining the optimal parameters to achieve thermal comfort in each room and identifying room orientations, material selection is based on four criteria: humidity regulation, thermal inertia, insulation type, and finish type.

The material selection for the room with the following optimized parameters was as follows:

Optimized parameters: Air speed: 0.05 m/s, Air temperature: 21 °C, Radiant temperature: 26 °C, Relative humidity: 60%, PMV = - 0.479 (slightly cool).

Insulation: Rock wool was chosen to reduce temperature fluctuations and maintain comfort. For east-facing walls, cellulose wadding was used due to its good thermal lag, along with wood fiber panels.

Thermal inertia: Concrete was selected for walls and slabs, as it stores heat during the day and releases it at night.

Humidity control: Lime plaster (for its moisture regulation) and wood (for its pleasant contact temperature and hygroscopic properties) were chosen for interior finishes.

Glazing: Solar control double glazing was selected to avoid overheating.

After carefully applying these material choices to the architectural model, a new verification analysis was performed, and the results on Figure 5 were obtained.

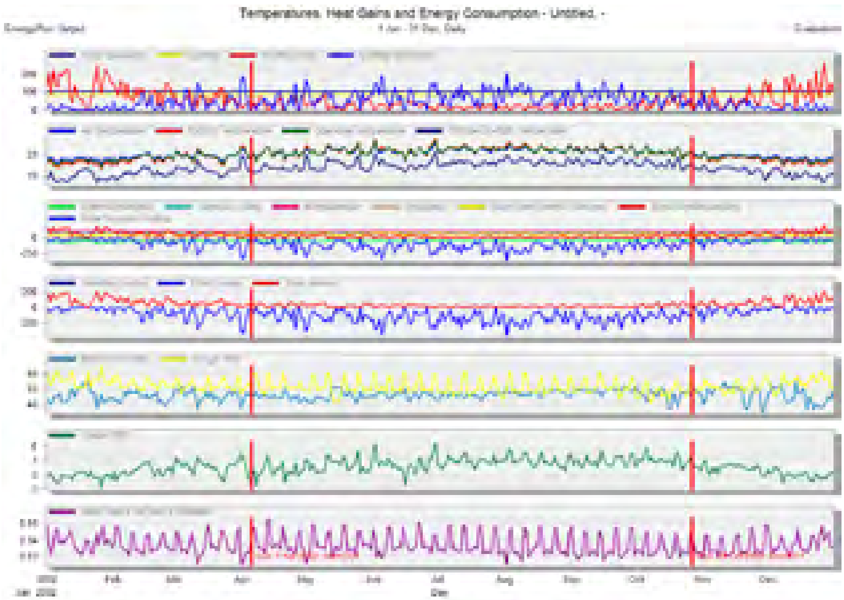

Figure 5: Thermal comfort evaluation results After optimization

5. DISCUSSION

The findings of this study clearly highlight the potential and practicality of a parametric optimization approach to assessing thermal comfort during the early stages of architectural design. By integrating Building Information Modelling (BIM) tools such as Revit with the visual programming environment of Dynamo and Python scripting, it becomes feasible to automate complex calculations and carry out early evaluations of key thermal comfort indicators, including air temperature, mean radiant temperature, air velocity, and relative humidity, in conjunction with occupant-specific factors such as clothing insulation and metabolic activity. This approach bridges the gap between architecture and environmental engineering, enabling architects to make informed design decisions without relying solely on external simulation tools or post-design evaluations. The model further demonstrates how orientation and solar exposure significantly influence thermal behaviour and should inform material selection within rooms according to their directional exposure. For instance, high thermal inertia materials such as concrete proved beneficial in south- and west-facing rooms to reduce overheating risks, while hygroscopic materials like lime plaster improved moisture regulation in enclosed or humid spaces such as bathrooms. The Predicted Mean Vote (PMV) index calculated for various room types consistently fell within the recommended range of -0.5 to 0.5, confirming that the optimization algorithm was effective in achieving thermally neutral conditions in line with EN15251 standards. Furthermore, the integration of EnergyPlus simulations with the Revit-based scripts served to validate the reliability of the optimized parameters in producing realistic thermal performance outcomes, thereby reinforcing the credibility and practical value of this methodology for design professionals. Nevertheless, it is important to acknowledge that the tool's accuracy remains contingent upon the quality of user-defined input parameters and underlying assumptions regarding occupant behaviour and site-specific climatic conditions.

6. CONCLUSION

In conclusion, this research offers a comprehensive, automated framework for optimizing thermal comfort in architectural models through the use of BIM technologies, specifically by leveraging the combined capabilities of Revit, Dynamo, and Python scripting. The proposed methodology significantly reduces the time and complexity typically associated with early-stage environmental analysis, while also enhancing the quality of design decisions by allowing practitioners to explore a range of configurations and material alternatives based on their thermal performance.

By integrating parametric scripts, shared parameters, and automated orientation recognition, this approach facilitates the creation of thermally responsive architectural models that comply with international standards for indoor environmental quality. The application to a multi-unit residential building illustrated the practical effectiveness of the method, where optimized parameter values led to the attainment of thermal comfort targets while also informing appropriate choices of insulation, thermal inertia, humidity control, and solar protection materials. This constitutes a meaningful step forward in embedding environmental considerations within the architectural design process, fostering a more sustainable and occupant-focused approach. Future developments could see the methodology expanded to include real-time climatic data, adaptive comfort models, or user-driven feedback loops, thereby extending its usefulness across diverse climates and building typologies. Ultimately, the study underscores the critical role of digital tools and parametric modelling in advancing energy-efficient, comfortable, and context-sensitive design solutions in the evolving field of performance-driven architecture.

REFERENCES

Alsharif, R. et al. (2021) 'A review of building parameters' roles in conserving energy versus maintaining comfort', Journal of Building Engineering, 35, p. 102087. doi: 10.1016/j.jobe.2020.102087

ANSI/ASHRAE/ASHE Standard 170–2013, Ventilation of Health Care Facilities; American Society of Heating, Refrigerating Air-Conditioning Engineers (2017).

ASHRAE (2017) ANSI/ASHRAE/ASHE Standard 170-2013, Ventilation of Health Care Facilities; American Society of Heating, Refrigerating Air-Conditioning Engineers.

Bianchini, G. et al. (2019) 'An integrated model predictive control approach for optimal HVAC and energy storage operation in large-scale buildings', Applied Energy, 240, pp. 327–340. doi: 10.1016/j.apenergy.2019.01.187

Bojic, M., Parvedy, A.P. and Boyer, H. (2013) Optimization of thermal comfort in building through envelope design.

Carli, R. et al. (2019 - 2019) 'Model predictive control for thermal comfort optimization in building energy management systems', 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy, 10/6/2019 - 10/9/2019: IEEE, pp. 2608–2613. doi: 10.1109/SMC.2019.8914489

Chen, Z., Tao, Z. and Chang, A. (06182021) 'A data-driven approach to optimize building energy performance and thermal comfort using machine learning models', Proceedings of the 2021 1st International Conference on Control and Intelligent Robotics, ICCIR 2021: 2021 International Conference on Control and Intelligent Robotics, Guangzhou China, 18 06 2021 20 06 2021. New York, NY, USA: ACM, pp. 464–469. doi: 10.1145/3473714.3473794

Eastman, C.M. (2011) BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors: John Wiley & Sons.

Fanger, P.O. (1970) Thermal comfort. Analysis and applications in environmental engineering. Available at: https://www.cabidigitallibrary.org/doi/full/10.5555/19722700268.

Hauglustaine, J.-M., Simon, F. and Monfils, S. (2018) La fenêtre et la gestion de l'énergie: SPW Energie, Namur, Belgium. Available at: https://orbi.uliege.be/handle/2268/248697.

Hawila, A.A.W. and Merabtine, A. (2021) 'A statistical-based optimization method to integrate thermal comfort in the design of low energy consumption building', Journal of Building Engineering, 33, p. 101661. doi: 10.1016/j.jobe.2020.101661

Houssam Affan (2024) Etude du comportement hygrothermique et durabilité de matériaux de construction incorporant des biomasses. Unpublished.

Kamel, E. and Memari, A.M. (2019) 'Review of BIM's application in energy simulation: Tools, issues, and solutions', Automation in Construction, 97, pp. 164–180. doi: 10.1016/j.autcon.2018.11.008

Patry, P.-M., Molle, D. and Sénova (2015) RT 2012 et RT Existant: Réglementation thermique et efficacité énergétique: Editions Eyrolles.

Rane, N., Choudhary, S. and Rane, J. (2023) 'Enhancing thermal comfort through leading-edge design, monitoring, and optimization technologies: A review', SSRN Electronic Journal. doi: 10.2139/ssrn.4642529

Schweiker, M., Rissetto, R. and Wagner, A. (2020) 'Thermal expectation: Influencing factors and its effect on thermal perception', Energy and Buildings, 210, p. 109729. doi: 10.1016/j.enbuild.2019.109729

Sibyan, H. et al. (2022) 'Thermal Comfort Prediction Accuracy with Machine Learning between Regression Analysis and Naïve Bayes Classifier', Sustainability, 14(23), p. 15663. doi: 10.3390/su142315663

UN Environment (NaN) Les émissions du secteur mondial du bâtiment restent élevées et continuent d'augmenter, 30 June.000Z. Available at: https://www.unep.org/fr/actualites-et-recits/communique-de-presse/les-emissions-du-secteur-mondial-du-batiment-restent (Accessed: 30 June 2025.849Z).

Wargocki, P. (2019) 'Productivity and Health Effects of High Indoor Air Quality', in Encyclopedia of Environmental Health: Elsevier, pp. 382–388.

TOWARDS A MULTIDIMENSIONAL REALITY: INVESTIGATING THE IMPACT OF VIRTUAL ENHANCEMENTS ON SPATIAL EXPERIENCE

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ABSTRACT:

This study explores the evolving conception of architectural space in the context of emerging digital technologies and their impact on spatial perception, bodily experience, and form-making. Departing from traditional architectural theories that emphasize predominance of the architect as the singular creator (Carpo, 2011), this research investigates how contemporary space-making practices are reshaped by virtual, augmented, and mixed realities (VESs). Drawing on foundational theories by Schmarsow and Schwarzer (1991), who emphasize the role of bodily movement and spatial intuition in architectural form, the study examines the interplay between bodily experience, spatial modulation, and the emergence of hybrid environments. This study aims to understand and examine the relationships between the spatial outcomes of real spaces and virtual spaces developed based on experience. In the context of spatial effects of real architectural spaces that referred to as analog spaces, the effects of virtual environments on space creation practices are discussed to reveal

possible correlations between real and virtual environments. By examining the spatial effects of analog spaces, the study investigates VESs to uncover potential correlations between physical and virtual realms, particularly in relation to their theoretical significance within space-making practices. Furthermore, by focusing on spatial experiences across different realities, study seeks to reveal the paradigm shift in the conceptual and principled understanding of space within contemporary architectural discourse. This study explores how virtual and analog spatial experiences shape architectural perception, how emerging technologies influence spatial creation, and the role of bodily interaction in multi-reality environments. It aims to bridge traditional architectural theory with digital spatial design, contributing to the interdisciplinary dialogue between architecture and media technologies. This paper focuses on the preliminary phase of the research which involves a preliminary case study conducted within a virtual environment. While the overall study includes both real and virtual environments, this paper seeks to introduce the research framework, methodology, and early findings which aims to structure the main case study phase. The preliminary phase of this research involves a case study that issues AKM Türk Telekom Opera Hall in a virtual environment, VR 360°, to evaluate spatial affects, with participants from design-related fields providing qualitative feedback through structured surveys. The findings aim to refine a labeled spatial affects list,constituted by design principles from Moussavi (2009), Wong (1972, 1993), and Ching (1979), which will serve as a foundational framework for subsequent phases of the research. Preliminary findings underscore the need for a deeper understanding of spatial affects and user experiences in hybrid environments, laying the groundwork for the main case study.

Keywords: Architectural Theory, Bodily Experience, Virtually Enhanced Spaces, Different Realities, Digitally Supported Spaces, Digital Technologies

1. INTRODUCTION

From the beginning of the conception of architecture and the corresponding modalities have varied depending on the zeitgeist but it is possible to suggest that the most significant ones are affected by the developments in technology and in-dept query of the phenomenon of space. This study seeks to elaborate the paradigm shift on the conception of space in the context of bodily movement within the conventional conception of space as the real environment to the different realities that articulated from the former practices. Furthermore, the correlation between bodily experience and spatial form will be discussed throughout the study to unveil the connotations of spatial formation of different space-making praxes. Therefore, to set ground for the conceptual framework, first; study attempts to unfold the idea of bodily experience and movement, second, analyzes the representation of space in different realities through defining the terminologies as analog and virtually enhanced space and their specifications on spatial modulation, and third, through the emerging theories and the changing perspectives of the conception of space, study confronts the modulation of space in various realities as virtual reality, augmented reality, and mixed reality to find correlation between analog spaces and VESs in the context of temporality, continuity, materiality, transitivity, performativity, and discreteness.

By the middle of the nineties, natural science scholars and philosophers started to probe the sensory aspects of space and the participation of human movement within space. It was inevitable and perhaps slightly delayed interest that the architectural form and space are no longer a rigid and singular conception in theory, regardless of the praxis in which the ideas do not thoroughly coincide. The most salient common concern for all is the articulation of space with the intertwine of feelings of the body and the architectural form. Architectural space is no longer a mere geometry, also a process that consists of movement within the affective experience of the body. Architectural space becomes an extension, an archetypal image of the human body. Schwarzer and Schmarsow (1991) asserts that bodily experience can be defined as an animate continuum that enables the spatial form to be generated by the association with human figure, motion, and nature whereas through the association with two vital sources of sensation as human body and senses with the states of physical environment, spatial intuition emerges. Departing from the idea of bodily experience and animation, different realities ground the articulation of space depending on the modulation, hence the movement in virtual mediums. These new realities reconstitute a living entity, a spatial enclosure through overriding or annexing the real environment. In this case, sometimes the analog or physical space has fragmented as in augmented reality whereas sometimes it is utterly discrete as in virtual reality. Regardless of the consequent status of different realities, all enact vitality through residing the body and various sensory modalities in which the perception of space expands and transforms through the movement and the shift in cognition. According to Sheets-Johnstone (2010), since from the innate nature of human beings' existence, people engage with the world not through embodiment but through movement where the animation takes place, and cognition should be associated with the animation that issues cognitions which emerges through affective sensory aspects.

2. THEORETICAL FRAMEWORK

In the context of a building as a design object and as an outcome-happening needs to be extensively defined to better serve the theorization of architecture in terms of tendency to interrelations, interconnections, closeness, intertwining, affinity, bordering within and with the buildings so that designed architectural theory relates with the building and its relational inhabitants and the inherent materiality (Crysler, Cairns, and Heynen, 2012). On the other hand, through deploying Deleuze's school of thought, Eisenman stresses the fact that conception of form can vary in diverse ways in which the finalized form is not discrete; it is a result related with the process of variation and in praxes architectural form results as the variety in motion that was symbolized through the form (Carpo, 2011). Literal or figurative metamorphosis of form whether through physically changing the form or to interpret metaphorically through the experience, it is not possible to refer form as a single and discrete being. The form hence the space becomes the realm of plurality where qualitative theory of space shifts towards the quantitative. It is possible to suggest that the unity of space and form with human mediation within space paves the way for a constant somatic and sensual flux in which the projections of space may have discrete connotations and imprints unique for one. These altered and re-defined spatial initiatives consequently depend on the lived experience, hence the state of affection. According to Ionescu (2016), architectural space ensured through the modulation of affectivity. Affective experience constituted around the movement of the body in space and the kinesthesia in which the perception of the environment varies synchronously. Therefore, the human body acts as a mediator or vehicle for the transmission; extends through space and enwraps the perception and experience altogether. Affection takes place in architectural space where the process becomes the space, and the space becomes the source of affectivity. The spectacle that architectural space possess justifies the affection while the experience legitimatizes the architectural form.

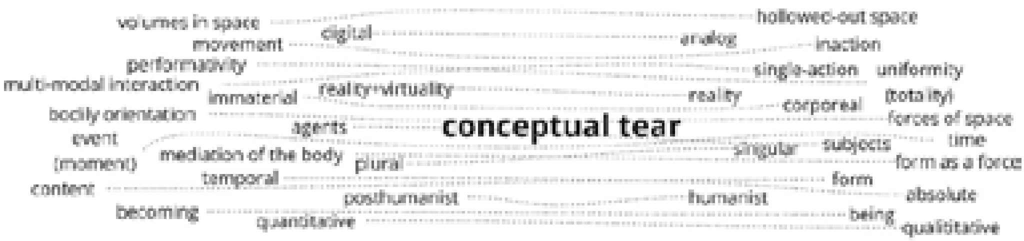

Figure 1: Agents and concepts of paradigm shift

Departing from the paradigm shift on the conception of space from singular, humanist, qualitative to plural, post-humanist, quantitative, the conceptual tear unfolds the discourse of architecture in the spatial conduct (Figure 1). Our intentional understanding of existence rely on categories that operates human perception such as ideal and real or general and specific in which perception, as our fundamental way of knowing, is inseparable from the inherent structure of the body and its interaction with the world and the body serves as the core from which all interpretations of the world arise; it not only exists in space and time but also embodies these dimensions (Pérez-Gómez, 1983). Since space is not reduced to a single realm, representation of space cannot have a mere connotation. Space ensures the possibility of accommodating various conceptions of space such as the imaginative, screened, cosmic and outer space as well as the physical space through the ambiguity it possesses in which space enacts as the mediator to eliminate the impasse amongst the abundance of real and mythic spaces (Beckmann, 1998).

With the collapse and turning point of modernism, the necessity of a reassessment of architectural theory has emerged. Furthermore, the context and the content of the architectural discourse are restricted by the limitations of form, which fetters architecture into shallow grounds where broader values such as culture, sociology, or political issues disregarded. According to Leach (1997), the public context of the current era is reflected by the architecture where these new conditions are protected by the act of consciousness towards modernism. The relationship between architecture and broader cultural, economic, and political forces, and how architecture can be understood as both a product and a reflection of these new conditions has become the pedestal of architectural discourse. Beyond the functional aspects of architecture, the effect on human experience, identity, and interrelations of social conduct embraced to implement sensory dimensions along with materiality. The body is accepted and evaluated as a shared site of social exchange and a pipeline of affectivity instead of being an autonomous entity in terms of corporality as a substitute to personalized being, in which the corporality associates with the inhabited environment repeatedly, further on language, by the gestures (Kwinter, 1989). Physically sustained body with its own periphery and interrelations becomes an affective and social conduct.

3. METHODOLOGY AND CASE STUDY DESIGN

This study explores how the perception of architectural space transforms when experienced in virtual environments compared to physical, analog settings. It investigates spatial affects, concepts that capture space's sensory and cognitive impact, through immersive user experiences. The research combines a VR-based user study with case study methodology, emphasizing qualitative interpretation of architectural form, composition, and atmosphere. The complete study includes two comparative groups and a preliminary pilot phase. The preliminary case study, which this paper focuses on, serves as a test environment to validate the spatial affect framework and survey tools within a realistic virtual context.

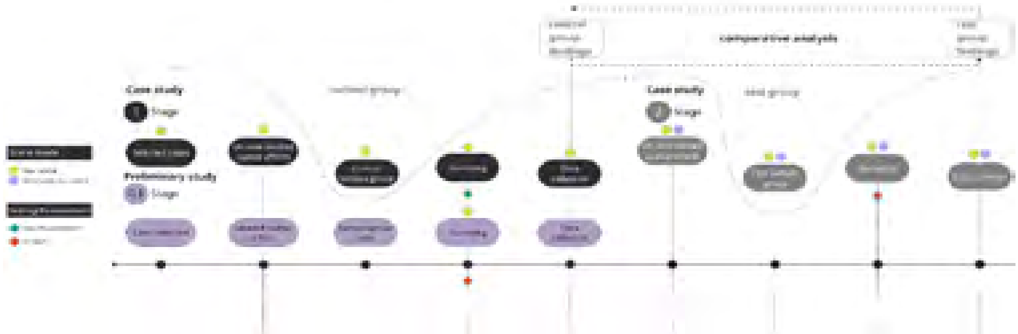

Figure 2: Case study process and terminologies

As shown in Figure 2 above, while the complete comparative structure involves on-site and VR-based spatial encounters, the preliminary study (0.1 stage) simulates one specific leg of this framework: the test group's experience of a realistic virtual representation of a selected real-world architectural space.

3.1. Research approach and scope

The study adopts a qualitative methodology, combining architectural theory, spatial design principles, and immersive VR-based user experience analysis. The research is situated within the discourse of VESs, which are treated not as evolving designs but as perceptually complete spatial environments. The aim is to understand how these environments compare to analog spaces regarding how users perceive, interpret, and emotionally respond to architectural conditions.

To that end, the full case study is built on a two-group structure:

- A control group which explores the real architectural space (AKM foyer) on-site without augmentation or digital manipulation.
- A test group which experiences same space in two different scene modes:
- A realistic virtual scene, a detailed digital twin based on high--fidelity 360° imagery.
- A semi-abstracted virtual scene, a conceptual version in which form-defining elements are emphasized while surface detail is minimized.

This paper is limited to the preliminary case study, which uses realistic virtual scene mode. It acts as a pilot phase conducted before the main study to refine the tools and ensure the theoretical and perceptual integrity of the spatial affect categories.

3.2. Preliminary case study

The preliminary case study is situated within the test group framework and replicates its first mode: a realistic, high-fidelity virtual representation of the selected space. The objective is to test the spatial affects classification, survey structure, and image-based evaluation flow before applying them to a broader sampler. It also helps to uncover early response patterns and confirm that the conceptual structure resonates with participants in a controlled, immersive VR setting.

The selected case is the Türk Telekom Opera Hall foyer within the Atatürk Cultural Center (AKM) in Istanbul. This space was chosen due to its:

- Public accessibility and central urban location,
- Volumetric richness in both horizontal and vertical dimensions,
- The presence of gallery openings and architectural depth,
- Geometric readability and abstraction potential,

- Minimal historical ornamentation, reducing interpretive bias.

115 panoramic 360° images of the AKM foyer were captured using an Insta360 X4 camera. These images were taken from different camera angles and spatial points to ensure broad spatial coverage. From these, 28 images were selected for the preliminary study. The selection emphasized frames that best represented the interior's spatial depth, openness, and organizational logic.

The preliminary test group includes three participants, all professionals from the architecture and design field. The selection was based on:

- Professional expertise, ensuring a capacity to recognize and articulate spatial relationships,
- Availability and convenience of access,
- Exclusion from the main study group to maintain independent observation.

The VR experience was conducted in the Bahçeşehir University Faculty of Architecture and Design VR Lab, using head-mounted displays in a seated, controlled environment. Each participant individually navigated through the 28 selected frames, presented as 360° immersive views, simulating a real walkthrough's spatial depth and orientation.

3.3. Instruments and Environment

Following the VR session, participants completed a structured online questionnaire (via Google Forms) to evaluate spatial perception through closed-ended checklists and open-ended reflection prompts. The survey focused on identifying perceived spatial affects in each frame and included Likert-scale questions to assess overall VR experience quality (e.g., realism, spatial presence, comfort). Based on Moussavi's (2009) list of affects that defined by Deleuze in terms of unmediated perception of built environment and form, Wong's (1972) and (1993) principles of two dimensional design and form and design, and Ching's (1979) architecture form, space and order, spatial affects are categorized and labeled in 7 categories as: composition defining (immaterial content), composition defining (corporeal content), form defining (absolute), form modification (passive, being, forces of form), form modification (active, becoming), axial position, and surface quality. The initial set of concepts used in preliminary study can be found in Table 1 below. Participants selected relevant affects for each scene and were given optional open-response fields to elaborate. Likert scale questions regarding overall VR experience were also included to contextualize engagement.

The responses collected were analyzed through the following steps:

- Thematic coding, to group recurring spatial affects across participants and images,
- Pattern recognition to identify scene-specific perceptual consistencies,
- Concept refinement eliminates ambiguous, redundant, or inconsistently used affect labels.

This phase led to refining the affect list and minor structural adjustments to the survey instrument. Concepts that were too vague or yielded highly variable responses were flagged for removal. In contrast, concepts were consistently recognized across frames, and participants were retained as core elements of the final analytical framework. The main comparative case study phase will apply the revised spatial affects list and survey format. This ensures continuity and reliability across both analog and virtual study conditions, supporting the investigation of how different modes of spatial experience affect architectural perception.

Category	Concepts
1. Composition Defining (Immaterial)	Lightness, Weightiness, Slenderness, Slowness, Hollowness, Broadness, Openness, Freedom, Infiniteness, Oneness, Deadness, Bluntness, Stability, Instability, Intricacy, Unity, Superunity, Affinity, Universality, Hovering, Floating, Encircling, Tenting, Fluctuating, Conflicting, Concentration, Over-concentration, Deconcentration, Attenuation, Association, Abstraction, Diffusion, Positive space, Negative space, Static, Focus, Closure, Enclosure, Movement, Monolith
2. Composition Defining (Corporeal)	Continuity, Discontinuity, Regularity, Irregularity, Symmetry, Asymmetry, Complexity, Informality, Versatility, Uniformity, Similarity, Monotony, Singularity, Minority, Majority, Plurality, Anomaly, Hierarchy, Repetition, Variation, Differentiation, Disorganization, Imperfection, Twistedness, Compoundness, Contrast, Occupied, Unoccupied
3. Form Defining (Absolute)	Horizontality, Verticality, Diagonality, Rectangularity, Triangularity, Pentagonality, Orthogonality, Conicality, Tubularity, Crystallinity, Vaulting, Latticing, Waffling, Ribbing, Diamonding, Hyper-curving, Roundness, Cavernousness, Amorphousness, Stellatedness, Polyhedrons, Plasticness, Lateralness, Striatedness, Straightness
4. Form Modification (Passive / Being)	Curving, Bending, Stretching, Pinching, Squeezing, Floating, Curling, Lacing, Dividing, Cutting, Removing, Combining, Interlinking, Arching, Faceting, Stacking, Folding, Layering, Inverting, Rippling, Distortion, Transformation, Deformation, Disintegration, Segmentation, Multiplication, Gradation, Subdivision, Subtraction, Intersection, Dislocation, Superimposition, Dilation, Inflation, Deflation, Rotation, Extension
5. Form Modification (Active / Becoming)	Bifurcation, Reticulation, Disruption, Transfiguration, Proliferation, Blasculation, Conglomeration, Undulation, Extrusion, Radiation, Intersection, Interpenetration, Deviation, Tension, Compression, Overlapping, Canceling, Touching, Branching, Scattering, Sliding, Fracturing, Tapering, Banding, Splitting, Tearing, Breaking, Creasing, Crossing, Detaching, Slanting, Cantilevering, Pointing
6. Axial Position	Centrality, Concentricity, Eccentricity, Centrifugality, Axiality, Bi-axiality, Directionality, Bi-directionality, Rectilinearity, Orientationality, Multilinearity
7. Surface Quality	Porosity, Granularity, Cellularity, Luminosity, Reflectivity, Matteness, Smoothness, Glossiness, Softness, Hardness, Roughness, Flatness, Undulating, Bubbling, Quilting, Stippled, Scratched, Embossed

Figure 3: Labeled spatial affects of preliminary case study

4. FINDINGS

The first phase of preliminary study starts with the real images of AKM without any abstraction. Furthermore, preliminary case study issues survey in two phases. In the first phase, survey includes open-ended questions which address space and form defining concepts and design principles. In addition, initial questions aim to measure and evaluate the overall VR experience. The second phase of the survey includes closed-ended questions issuing the labeled spatial affects (Figure 3) as checkbox answers. Users are asked to start with the first phase survey questions, without any given spatial affects, with open-ended questions. Followingly, at the second phase, users are asked to select from the given spatial affects in checkboxes, with closed-ended questions. With the proposed two-phase survey, the study intends to reveal the potential of labeled spatial affects list through comparing the findings of open-ended and closed-ended questionnaire. The second phase of the survey contains seven categories within the closed-ended questionnaire as composition defining (immaterial content), composition defining (corporeal content), form defining (absolute), form modification (passive, being, forces of form), form modification (active, becoming), axial position, and surface quality. Participants were asked to complete the first survey with open-ended questions to start with, then were given the second survey with closed-ended questions to prevent pre-codes and biases.

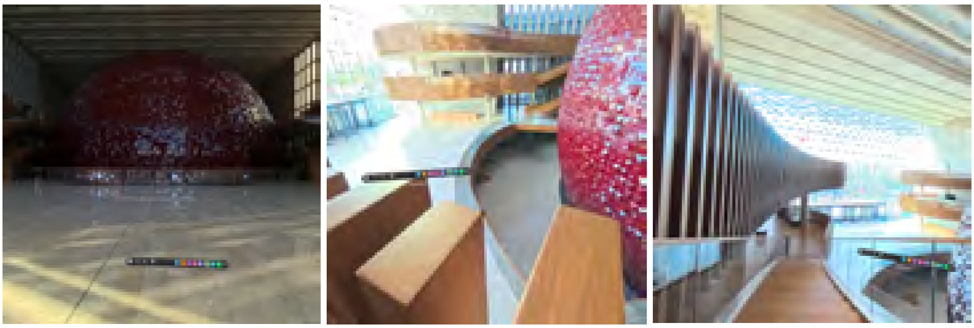

Figure 4: Participant 2 VR experience screenshots

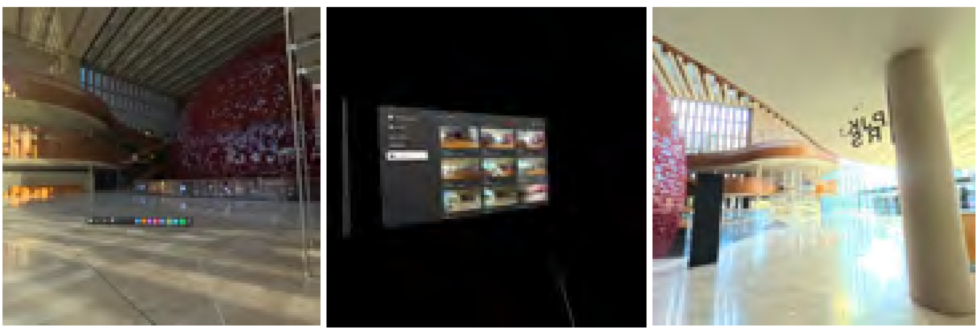

Figure 5: Participant 3 VR experience screenshots

Three participants of preliminary case study indicate their ages as 31, 34, and 35 in the first question of the questionnaire. Participants in the profession of architecture or interior architecture had 5 to 10 years of experience participated in the survey, stating their frequency of VR usage as rarely in domains as gaming, cultural, educational, travel, and simulations. Following questions issues 1-10 likert scale evaluation regarding the experience of the virtual environment and setup. Participants evaluated their overall VR experience and perception by rating within the range from 5 to 9, stating different levels of satisfaction, but stated that the immersion levels of the VR experience indicate participants are generally pleased with the VR engaging experience by the range of 7 to 9. Conversely, participants indicate that VR experience had some usability issues in terms of navigation and interface, ranging between 6 to 8 scale. Regarding physical comfort, hardware related problems are stated by one participant while another indicated the need for more freedom in movement. Furthermore, physical discomfort is stated but not dwelled on in the follow-up open-ended question. For the evaluation of VR hardware and the technical equipment capabilities, two of the participants indicated their level of satisfaction with the scale from 9 to 10, while the other participant stated the level of satisfaction with the scale of 5. When elaborated separately, the participant who stated medium levels of satisfaction indicated the overall experience on VR and the level of immersiveness in the range of 8 to 7, therefore it can be suggested that the participant was pleased with overall experience in despite of stated issues. The performance of VR software meets expectations with higher levels of satisfaction rates. All three participants indicated that they were highly focused while using VR with the rates of 8 to 10. Only one participant has been to AKM before and stated the effectiveness of VR in understanding the issued space compared to traditional methods effective to a great extent.

The improvements that need to be adapted can be stated as to address the issue in navigation and movement in VR environment and to increase the spatial fidelity and representation through enhancing transitions between selected images of AKM and increasing the realism. Physical comfort related issues cannot be improved due to feasibility issues. The first set of questions regarding the experience measurement first is intended to identify the users and second to evaluate the overall VR experience.

Following questions within the first phase of the questionnaire probes the experience of the participants of the selected space as AKM. These questions are open-ended questions, which entangles the same concepts as the second phase of the questionnaire with close-ended questions. Participants are asked to write concepts that they can refer to related to the categories. Highlighted concepts for composition definition, covering category 1 and 2 together, were color, volume, spatial hierarchy, symmetry. Hierarchy, symmetry and color were recurring themes for most of the participants in which segmentation and sequences of space play a role. In form defining concepts, regarding category, sphere emerged as the most dominant element where users defined and described the rest of the concepts around the centrality of sphere mostly. The focal point of the given space as the sphere was acknowledged by the participants along with curvilinear forms. In addition, usage of the term enclosure may have suggested that participants can understand the spatial boundaries in VR environment. Void, subtraction, horizontality, surface manipulation, contrast are stated as the most prominent features of the form modification concepts, category 4 and 5, in which the sensitivity to surface qualities in VR environments is assured. Furthermore, the participant who can identify the voids and subtractions may successfully assess the negative space in a virtual environment that validates the reliability of VR in terms of decoding the architectural space and acknowledging volumetric boundaries. For the axial relations, category 6, symmetry is highlighted by two participants. The other participant indicated that the central structure of the space dictates certain axial relations but does not dominate the overall circulation. For category 7, the recurring surface qualities, highlighting glossiness and shiny surfaces along with differentiation in patterns and textures as softness and wood, ensuring the rendering qualities of VR environments in terms of materiality.

For the second survey, to ease the participants' selection from given concepts, seven categories are re-grouped as subcategories. These subcategories are based on semantic relations and presented to the participants with checkbox answer options. Second phase of the questionnaire findings which issues closed-ended questions are as follows:

Group 1 which entails composition defining concepts in immaterial content. Most attributed concepts were highlighted as hollowness, broadness, openness, stability, intricacy, unity, universality, floating, encircling, abstraction, negative space, static, focus, enclosure, and monolith. For group 2, which entails composition defining concepts in corporeal content, participants identified the recurring themes as follows: regularity, symmetry, similarity, singularity, hierarchy, repetition, differentiation, contrast, and unoccupied. For group 3, form defining concepts, verticality, rectangularity, cavernousness, roundness, ribbing, and striatedness were the most referred terms. Group 4 which entails form modification in the sense of passive, being, forces of form. Recurring terms were curving, interlinking, multiplication, subtraction, superimposition, and inflation. In respect to the findings of group 3 and group 4, a significant number of given concepts occurs redundant. For group 5, form modification in the sense of active, becoming in which interpenetration, overlapping, banding were the most prominent terms as stated by the participants. Most of the concepts given appear forced and irrelevant or might be too vague to depict. The findings of group 6 indicate that centrality, axiality, rectilinearity, and orientationality were the concepts which are predominant for the issued space. Furthermore, participants were able to depict the dominant focal points and hierarchical organization that implies connotations of spatial orientation and structural alignments in VR environment. The last group of the survey is issued under group 7 where the surface qualities of the given space are probed. Participants highly engaged with the terms mattness, smoothness, glossiness, softness, hardness, undulating, and embossed.

4.1. Case review

Based on the findings of these three participants, matters that need attention to refine the case study are highlighted in two titles as follows:

Content related issues

- Participants had difficulty understanding the content and the context of the questions of first phase. Furthermore, compared to the second phase of the study, which issues closed-ended questions, participants spent more time answering the questions. Due to clarification and vagueness issues, the first phase of the study should be eliminated.
- The number of spatial affects issued in the second phase of the study was too much and some concepts were too irrelevant to the subject. Accordingly, the labeled spatial affects list needs to be refined in terms of the number of categories and the issued concepts.

VR hardware/software (Meta Quest 2) issues

- 360 ° photo files can be viewed one by one without any sliding option. Also, although the files are saved in numerical order, VR documents do not arrange them in the proper order. A more user-friendly approach can be adopted to ease and refine the experience.

Moreover, regarding the refinement of content related issues, the first tailoring is based on the labeled spatial affect list as mapped out beforehand. To refine and finalize the spatial affects list as to be on-task set of concepts (Figure 6), first, the spatial affects under each category is analyzed and eliminated by the findings and depending on their relevancy to the issued space semantically. Followingly, for further refinement, remaining spatial affects are re-grouped and re-named for clarification. New groups are under six new categories as spatial qualities and perception, spatial organization and relations, directionality and geometrical properties, form and transformation, structural and axial properties, and material and surface qualities. The second elimination is based on cross-matching the issued spatial affects between new categories.

Group 1 Spatial qualities and perception	Lightness, Broadness, [illegible], Universality, [illegible], Openness, [illegible], Hovering, Slenderness, [illegible], Unity, [illegible], Affinity
Group 2 Spatial organization and relations	Continuity, Complexity, Hierarchy, Uniformity, Discontinuity, Singularity, Variation, Symmetry, Plurality, Contrast, Asymmetry, Anomaly, Repetition
Group 3 Directionality and geometric properties	Horizontality, Crystallinity, Amorphousness, Verticality, Latticing, [illegible], Diagonality, Hyper-Curving, [illegible], Rectangularity, Roundness, Straightness
Group 4 Form and transformation	Bending, Dividing, Layering, Multiplication, [illegible], Extrusion, [illegible], Sliding, Dissolving, Stretching, Combining, Distortion, Gradation, Disruption, Radiation, Overlapping, Tapering, Detaching, [illegible], [illegible], Disintegration, Subtraction, Transfiguration, Intersection, Touching, Banding, Lacing, Folding, Segmentation, Rotation, Undulation, Interpenetration, Branching, Tearing
Group 5 Structural and axial properties	Centrality, Axiality, Directionality, Rectilinearity
Group 6 Material and surface qualities	Porosity, Softness, Cellularity, Hardness, Glossiness, Roughness, Matteness, Smoothness

Figure 6: On-task labeled spatial affects

5. DISCUSSION

The preliminary case study has demonstrated that even a relatively passive VR360° environment, with minimal interaction, can convey key spatial affects and architectural qualities when coupled with a structured evaluation framework. Participants could identify composition, form, and material attributes effectively, confirming the viability of immersive image-based VR for spatial perception studies.

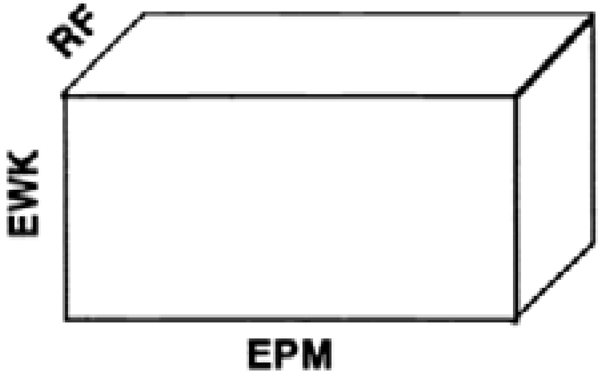

Figure 7: Three-dimensional taxonomic framework for classification Mixed Reality (MR) displays [Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1994), "Augmented reality: A class of displays on the reality-virtuality continuum" 1994]

Departing from Figure 7, the three-dimensional taxonomy based on three prominent features, Extent of Procedural Mastery (EPM), Reproduction Fidelity (RF), and Extent of World Knowledge (EWK), the study also reflects on how the current VR360° environment can be improved to reach a more balanced and immersive experience. The extent of procedural mastery represents the level of immersiveness or involvement of the users within the issued space, in which the higher values refer to high levels of control; reproduction of fidelity focuses on the quality of the displayed image in virtual environments in the levels of altering the real world effectively, where higher values indicate more sensible and immersive engagements; and extent of world knowledge involves the known information based on accuracy of displayed objects, in which as the value increases, the level of understanding the real world and the elements within increases along.

- High RF with ultra-realistic visuals may have low EPM, hence real-time interactivity.
- High EWK may cause low usability with poor intuitive controls due to extreme environmental awareness and complexity.
- High EPM without high levels of RF and EWK cannot meet the level of immersiveness where the user feels disconnected. Therefore, EPM should be balanced with realism.

Consequently, high RF and EWK together with EPM indicate a passive system with no interaction, and high EPM together with low RF and EWK indicate a detached system from reality.

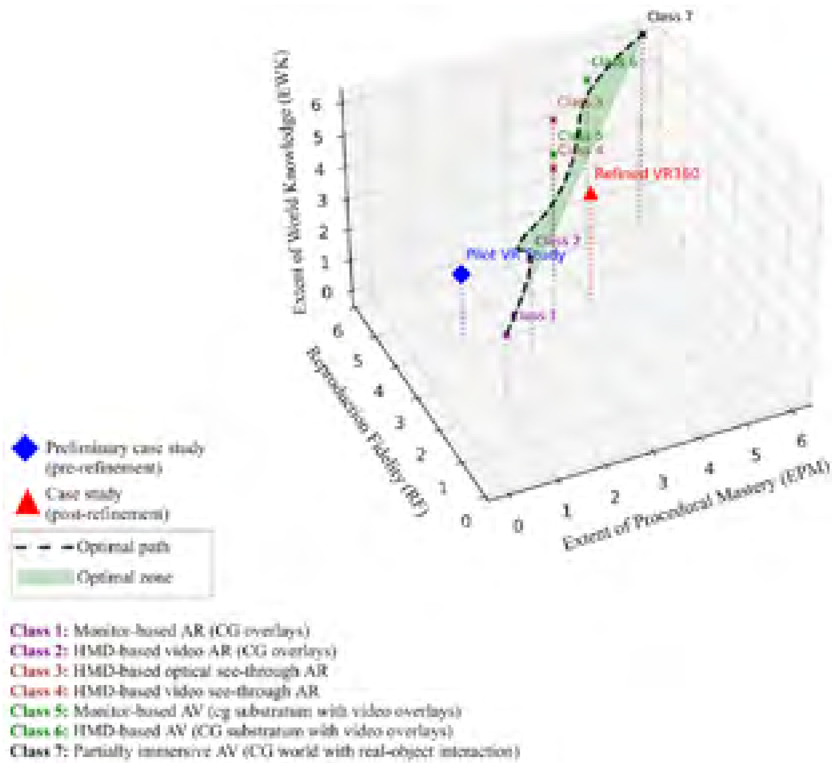

Figure 8: Pre and post refinement conditions of VR360° on overlayed 3D taxonomic representation

Figure 8 reveals the optimal zone for MR evolution by balancing all three features. This potential outcome can also be a valid departure point for VR systems. Since extreme levels of realism can interfere with usability, an approach to maintain realism and intuitive interaction must be employed. Furthermore, to balance the interaction freedom, capability assessment of the users must be considered to eliminate extreme precision requirements. On the other hand, since VR360° prioritizes RF, EPM is limited due to a lack of user interaction. EWK is issued at middle rates through capturing real-world images but lacks adaptive interactivity in which the user movement awareness is non-existent. Overall, it is an immersive experience with low levels of interactivity. To improve VR360° towards the optimal trajectory, experience in terms of interaction can be supported by hotspot-based navigation and real-time object interaction approaches. In this respect, teleportation and information hotspots are integrated into the case study. Consequently, these enhancements fulfill better user engagement and accessibility and reduce motion sickness due to artificial movement through controlled jumps between pre-defined viewpoints. In addition, the proposed system enables an experience where structured navigation is adapted, which enables feasibility for both test and control group users.

6. CONCLUSION

This study explores how virtual architectural environments, specifically 360° VR simulations, can serve as effective platforms for evaluating spatial perception and affect. The findings from the pilot phase confirm that labeled spatial affect frameworks are perceptually valid within VR contexts and that participants can identify architectural features such as hierarchy, materiality, and enclosure through immersive, non-interactive imagery.

The main constraints regarding the conducted study include:

- The case study is limited to one selected representative space (AKM).
- Dependence on the technological literacy of participants.
- VR simulation depends on 360° imagery, which may not fully replicate real-life experiences.
- Potential biases in spatial perception due to the virtual experience.
- The feasibility of conducting large-scale VR-based studies.
- Limited accessibility to specific real-world spaces for comparison.
- Sampling constraints may affect generalizability.

Despite such limitations, research has established a strong foundation for the technical and conceptual framework for future comparative studies. The synthesis of navigation updates and user-defined modes of interaction is clear in its approach to balancing procedural usage and sensory accuracy. With future work moving into the main stage of real-world and virtual environment comparison, ongoing research will support closer explorations of how spatial affects occur across experiential worlds. Finally, for the first time within VR research and application, VR is conceptualized as a representation tool and active, affective process for space conception research, capable of mediating the process of conception of space in the post-digital era.

REFERENCES

Beckmann, J. (1998). The Virtual Dimension: Architecture, Representation, and Crash Culture.

Carpo, M. (2011). The alphabet and the algorithm. MIT Press.

Ching, F. D. K. (1979). Architecture: Form, Space, and Order. Van Nostrand Reinhold.

Crysler, G., Cairns, S., and Heynen, H. (2012). The sage handbook of architectural theory. Sage Publications.

Ionescu, V. (2016). Architectural Symbolism: Body and Space in Heinrich Wölfflin and Wilhelm Worringer. Architectural Histories, 4(1), p.10.

Kwinter, S., N. (1989). Immanence and Event in Early Modernist Culture. PhD Dissertation. Graduate School of Arts and Sciences, Columbia University.

Leach, N. (1997). Rethinking Architecture: A Reader in Cultural Theory (1st ed.). Routledge. https://doi.org/10.4324/9780203975251

Milgram, P., Takemura, H., Utsumi, A., and Kishino, F. (1994). A Taxonomy of Mixed Reality Visual Displays. IEICE Transactions on Information and Systems, 77, 1321-1329.

Moussavi, F., and López, D. (2009). The function of form. Barcelona: Actar.

Pérez-Gómez, (1983). Architecture and the crisis of modern science. Cambridge, Mass: MIT Press.

Schwarzer, M.W., & Schmarsow, A. (1991). The Emergence of Architectural Space: August Schmarsow's Theory of "Raumgestaltung". Assemblage, 48.

Sheets Johnstone, M. (2010). Body and movement: Basic dynamic principles. In Schmicking, D. and Gallagher, S. (Eds.) Handbook of Phenomenology and Cognitive Science, Netherlands: Springer, 217–234.

Wong, W. (1972). Principles of Two-Dimensional Design. Wiley.

Wong, W. (1993). Principles of Form and Design. Wiley.

TEACHING ARCHITECTURAL FEATURES: FROM TEXTBOOKS TO VIRTUAL WORLDS THROUGH IMMERSIVE GAMING

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ABSTRACT:

This research explores how gamification can be leveraged in architectural education by focusing on the impact of immersive video games, specifically Assassin's Creed Odyssey, on learners' ability to recall architectural details and comprehend spatial relationships. The primary objective is to assess whether engaging in architectural environments in a virtual setting leads to improved educational outcomes compared to conventional instructional approaches.

To achieve this, the study involved 20 participants with varied academic and professional backgrounds, ensuring a diverse sample for a more comprehensive evaluation of different teaching strategies among individuals without formal architectural training. Participants were randomly divided into two groups of 10. The experimental group navigated the Discovery Mode of Assassin's Creed Odyssey, spending approximately 30 minutes exploring architectural elements within the game's digital

world. Meanwhile, the control group received only the written transcript of the game's narration, accessing the same information in a purely textual format, without any interactive or visual engagement.

Neither group was provided with prior knowledge about the topic, ensuring an unbiased starting point. After the intervention, both groups completed post-intervention assessments consisting of multiple-choice questions aimed at measuring their learning. While the test formats differed, the content of the questions remained consistent to allow for direct comparison.

The resulting data were analyzed and visualized through graphs to aid interpretation. The outcomes were then reviewed to compare the effectiveness of game-based and text-based learning environments in promoting the recognition and understanding of architectural concepts. The results highlight significant considerations for educators and game designers, emphasizing the value of video games and alternative teaching methods in architectural instruction. Ultimately, this study adds to the growing body of research on educational innovation and provides meaningful perspectives on how immersive and text-based experiences influence the learning of complex topics.

Keywords: Immersive Learning, Game-Based Instruction, Architecture Pedagogy, Virtual Environments, Spatial Awareness, Assassin's Creed Odyssey

1. INTRODUCTION

The integration of gamification into educational practice has become increasingly prominent, especially in disciplines that demand spatial reasoning and experiential engagement (Deterding et al., 2011; Hamari et al., 2014). Gamification, the application of game mechanics in non-game contexts, has been shown to foster motivation, engagement, and improved learning outcomes across a range of fields In architectural education, where the comprehension of spatial relationships and the retention of visual and structural details are fundamental, immersive digital environments offer a promising bridge between abstract theory and hands-on experience (Saghafi et al., 2012; Salama, 2015).

Assassin's Creed Odyssey, particularly its Discovery Mode, exemplifies the potential of virtual environments to support architectural pedagogy. By enabling users to explore historically accurate reconstructions of ancient Greek architecture, the game provides a unique platform for experiential learning (Champion, 2015; Mortara et al., 2014). Kolb's (1984) experiential learning theory underscores the value of learning through direct experience, a principle that aligns closely with the affordances of interactive digital environments (Kolb, 1984; Schön, 1983). Research in educational technology has demonstrated that such environments can enhance spatial memory, deepen understanding, and increase learner engagement (Gee, 2003; Mikropoulos & Natsis, 2011).

Despite these advances, the comparative effectiveness of immersive, game-based learning versus traditional, text-based instruction in architectural education remains underexplored (Abdelhameed, 2013). This study addresses this gap by examining how different instructional modalities, interactive gameplay and textual learning, affect the acquisition of architectural knowledge and spatial cognition among learners from diverse academic backgrounds. By employing a mixed-methods approach, the research aims to provide nuanced insights into the pedagogical value of gamification in architecture, contributing to the expanding literature on innovative educational strategies (Maher et al., 2013).

2. LITERATURE REVIEW

The evolution of architectural pedagogy has been shaped by a continuous search for methods that foster both conceptual understanding and practical skills (Salama, 2015). Traditional studio-based learning, while effective in cultivating design thinking, often struggles to provide students with direct, embodied experiences of architectural space (Schön, 1983; Maher et al., 2013). Recent advances in digital technology have introduced new possibilities for experiential learning, particularly through the use of virtual environments and serious games (Champion, 2015; Mortara et al., 2014).

Gamification in education has been widely studied, with evidence suggesting that game-based approaches can enhance motivation, engagement, and knowledge retention (Deterding et al., 2011; Kapp, 2012; Hamari et al., 2014). In the context of architecture, immersive digital tools have been shown to support the development of spatial cognition, a core competency for architects (Abdelhameed, 2013). Virtual reality and game-based platforms allow learners to interact with architectural spaces, manipulate perspectives, and experience design elements in ways that traditional methods cannot replicate (Mikropoulos & Natsis, 2011; Saghafi et al., 2012).

Despite these benefits, the integration of gamification into architectural curricula remains limited, and empirical studies comparing its effectiveness to conventional approaches are scarce (Poggiolesi, 2016; Salama, 2015). This study builds on existing research by directly comparing game-based and text-based learning modalities, with a focus on their impact on spatial understanding and engagement among non-specialist learners.

3. METHODOLOGY

A mixed-methods research design was adopted to evaluate the comparative effectiveness of game-based and traditional learning approaches in architectural education. The study targeted participants with no prior design training to isolate the effects of the instructional modality. Twenty graduate students from non-design disciplines, aged 18–35, were recruited and randomly assigned to either an experimental group (n=10) or a control group (n=10). Gender balance was maintained to control potential biases.

The experimental group engaged with the Discovery Mode of Assassin's Creed Odyssey for 30 minutes, exploring three key modules: "The Akropolis of Athens," "The Agora of Athens," and "The Urban Household." The control group received a transcript of the in-game narration covering the same content, ensuring parity in informational exposure.

Following the intervention, all participants completed a post-test survey comprising 9 theoretical and 20 spatial comprehension multiple--choice questions. The survey was administered via Google Forms, with separate links for each group to facilitate data collection. Quantitative data from the post-test were analyzed to assess knowledge gains and spatial understanding across the two instructional modalities.

4. THEORETICAL FRAMEWORK

The study is grounded in experiential learning theory (Kolb, 1984), which posits that knowledge is constructed through direct experience and reflection. In architectural education, this approach is particularly relevant, as the discipline requires the development of spatial awareness and the ability to mentally manipulate complex forms (Salama, 2015;

Schön, 1983). The use of immersive digital environments aligns with constructivist principles, enabling learners to actively engage with content, make decisions, and construct meaning through interaction (Gee, 2003; Mikropoulos & Natsis, 2011).

Game-based learning environments, such as Assassin's Creed Odyssey, offer opportunities for embodied cognition, where learners' actions within the virtual space contribute to deeper understanding (Champion, 2015; Mortara et al., 2014). This theoretical perspective informs the study's design and interpretation of results, emphasizing the value of active participation and contextualized learning in architectural pedagogy.

5. IMPLEMENTATION

5.1 Participants

The study included 20 participants between the ages of 18 and 35. To ensure a diverse and heterogeneous sample, individuals were selected from various professional backgrounds and undergraduate fields. This approach was intended to minimize potential biases related to prior familiarity with architectural concepts. Participants were randomly assigned to either the experimental group (n=10) or the control group (n=10). Gender distribution was balanced to prevent any gender-related differences in learning preferences or outcomes. All participants were graduate students from non-design disciplines, ensuring that their exposure to architectural concepts was limited solely to the interventions provided during the study.

5.2 Study Procedure

Participants were randomly assigned to either the experimental or control group. The experimental group navigated the Discovery Mode of Assassin's Creed Odyssey, exploring three modules that provided immersive experiences of ancient Greek architecture and daily life. The control group read a transcript of the same content, presented in a non-interactive, text-based format.

5.3 Assessment

A post-test survey, divided into theoretical and spatial sections, was administered to all participants. The theoretical section assessed recall of factual and conceptual information, while the spatial section evaluated participants' ability to interpret and mentally manipulate architectural spaces. The survey covered the Akropolis of Athens, the Agora of Athens, and the Urban Household, ensuring comprehensive coverage of the content.

6. STUDY DESIGN AND IMPLEMENTATION

The test design was structured to compare the learning outcomes of game-based and traditional text-based methods in teaching architectural features. The experimental group played the Discovery Mode of Assassin's Creed Odyssey, exploring three distinct features designed to provide an immersive understanding of Ancient Greek architecture and daily life.

A common critique of game-based learning studies is the suggestion that similar educational outcomes could be achieved simply by presenting the same content through video, without the need for interactive gameplay. However, this perspective overlooks the fundamental differences between passive observation and active engagement. In the context of this study, the Discovery Mode of Assassin's Creed offers a level of interactivity that cannot be replicated by video alone. Participants are not merely passive recipients of information; instead, they actively navigate the virtual environment, make decisions about where to go, and engage directly with architectural spaces.

The first feature, "The Akropolis of Athens," found under the Famous Cities section, focused on the Parthenon, a monumental symbol of Ancient Greek civilization. Participants examined its intricately carved exterior, depicting mythological scenes such as the birth of Athena and the Panathenaic procession, as well as its interior, which housed a statue of Athena, emphasizing the artistic and cultural significance of Athens.

In the virtual environment of the Acropolis, participants are initially presented with a wide-angle overview that highlights the areas to be explored. Specific locations within the Acropolis are marked, indicating the points where participants are required to pause. At these highlighted spots, users stop and engage in an exploration of space, allowing for a focused examination of architectural and historical features.

After pausing at these designated points, participants continue their journey through the environment, interacting with the surroundings and various features. For example, they can enter the Parthenon, where they are able to perceive the scale of the structure and directly experience its architectural elements. This process of moving through the space, stopping at key locations, and interacting with the environment provides a dynamic and immersive learning experience that enables participants to develop a deeper understanding of both the spatial organization and the distinctive features of the Acropolis.

Figure 1: Insights from the "Acropolis of Athens"

The second feature, "The Agora of Athens" introduced participants to the civic and social hub of the city, where citizens, merchants, and philosophers gathered. Key elements included the Painted Stoa, renowned for its military-themed artwork and philosophical importance, the Hephaisteion temple dedicated to Hephaistos and Athena, and the Bouleuterion, the meeting place of the Athenian council, showcasing the democratic and cultural life of the city.

When exploring the Painted Stoa, participants can approach the murals, observe details from different angles, and interact with the environment in ways that foster a deeper spatial and experiential understanding. This kind of embodied interaction allows users to construct knowledge through direct experience, aligning with experiential learning theories that emphasize the importance of active participation in the learning process.

Within the Agora of Athens, participants are able to move freely through the marketplace. They can navigate among the stalls, observe the activities of various vendors, and experience the spatial organization and social dynamics of the agora in real time. This real-time exploration allows learners to choose their own paths, pause to examine specific details, and immerse themselves in the everyday life of the ancient city. The presence of animated vendors and market-goers provides a dynamic and authentic atmosphere that cannot be conveyed through static video footage. The learner's ability to control their movement and perspective within the space fosters a sense of presence and engagement that is fundamentally different from watching a pre-recorded sequence.

Additionally, the experience within the Bouleuterion further demonstrates the depth of interaction possible in the game environment. Participants can enter the Bouleuterion and attend events that are taking place inside. They have the opportunity to engage in conversations with non-player characters, listen to the discussions and debates occurring among the citizens, and observe the rituals and procedures of civic life. This interactive participation allows learners to not only witness but also take part in the social and political processes of ancient Athens. The ability to listen to conversations and interact with historical figures provides a level of immersion and contextual understanding that is unattainable through video alone. In the agora, the participant's viewpoint is situated among the market stalls, surrounded by vendors and goods, highlighting the immediacy and authenticity of the experience. In the Bouleuterion, the participant is positioned within the assembly, able to observe and listen to the proceedings, further emphasizing the participatory nature of the environment.

Figure 2: Insights from the "The Agora of Athens"

The third feature, "The Urban Household" provided insights into the design and function of Greek homes, or oikos, which revolved around a central courtyard. Participants explored spaces such as the andron (men's quarters for symposia), the gynaikonitis (women's quarters), and functional areas like the kitchen and bathroom, reflecting the social structure, gender roles, and practical aspects of domestic life in Ancient Greece.

Within the inner courtyard, participants can freely navigate the space, experiencing its layout and atmosphere firsthand. The environment is not static; learners can approach and interact with specific features, such as the sacred pool dedicated to Zeus located at the center of the courtyard. This interaction is not merely visual—participants can pause, examine the pool's details, and receive contextual information about its religious significance, deepening their understanding of ancient Greek spiritual practices.

In the kitchen area, the experience extends beyond architectural observation to include cultural immersion. Participants can witness the preparation of food, observing the tools, ingredients, and methods used in ancient Greek cuisine. This direct exposure allows learners to gain insights into the Greek diet, culinary traditions, and daily life, which would be difficult to convey through video alone. The ability to move around the kitchen, observe the cooking process from different angles, and receive explanations about the food being prepared creates a multisensory learning experience.

The women's quarters, or gynaikonitis, offer another layer of interactive learning. Here, participants can observe women gathered together, engaged in conversation. The environment allows learners to not only witness these social interactions but also to join the group, listen to their discussions, and even participate in the conversation. This level of engagement provides a unique perspective on gender roles, social customs, and the private lives of women in ancient Greek society. The opportunity to interact with non-player characters in this context fosters empathy and a deeper, more nuanced understanding of historical social dynamics.

Figure 3: Insights from the “The Urban Household”

The control group, in contrast, engaged with the same content presented in the game, but in the form of a transcribed text. This text was organized according to the sequence of gameplay and provided an exact, verbatim transcript of the information delivered by the in-game guide, ensuring that the control group received identical content to that experienced by the experimental group, but presented in a non-interactive, text-based format.

7. SURVEY DESIGN AND CONTENT

The survey questions were structured in two distinct parts to comprehensively assess participants' knowledge and understanding of the architectural, cultural, and spatial aspects of Ancient Greek spaces explored during the intervention. Part 1 consisted of theoretical questions, while Part 2 focused on spatial comprehension. The survey, administered via Google Forms (For the detailed information about survey, please see the Appendix A: Survey Instrument), included only multiple-choice questions and covered three main areas: The Akropolis of Athens, the Agora of Athens, and the Urban Household. To ensure consistency, the same survey was used for both groups, with separate links for the text-based and game-based learners to facilitate data collection specific to each learning method.

In the first section, the theoretical questions assessed participants' recall of factual and conceptual information. For example, participants were asked about the architectural features and mythological carvings of the Parthenon, the materials and purpose of the statue of Athena, and the symbolic significance of various structures. Additional questions addressed the civic, commercial, and social functions of the Agora, as well as the roles of specific buildings such as the Painted Stoa, Bouleuterion, and Heliaia. For the Urban Household, theoretical questions covered the design and layout of Greek homes, including the functions of the andron (men's quarters), gynaikonitis (women's quarters), and the significance of household spaces like the kitchen and bathroom. Cultural practices, such as the symposium and aspects of the Greek diet, were also included.

The second section focused on spatial comprehension and the participants' ability to understand and interpret the organization and use of space within these ancient environments. Questions in this section required participants to identify the locations of specific features within the Akropolis, Agora, and Urban Household, interpret spatial relationships, and recognize the functions of different areas based on their layout. For example, participants were asked to determine where certain activities took place, how spaces were accessed or connected, and to visualize the arrangement of architectural elements within the sites.

By dividing the survey into theoretical and spatial parts, the study ensured a balanced evaluation of both factual knowledge and spatial understanding.

8. DATA ANALYSIS & RESULTS

The results of the post-test survey compare the performance of the game-based and text-based groups across two sections: theoretical questions and visual-spatial comprehension questions.

In the game-based group, responses were notably more balanced, with most participants providing correct answers in both sections. For the visual and spatial questions, this group achieved consistently high accuracy rates, typically between 80% and 100%. This indicates a strong and uniform understanding of spatial relationships and visual features, likely supported by the interactive and immersive qualities of the game environment. In the theoretical section, the game-based group also performed well, with correct response rates generally ranging from 60% to

90%. These results suggest that the contextual and visual cues provided by the game not only enhanced spatial learning but also facilitated the retention of theoretical knowledge.

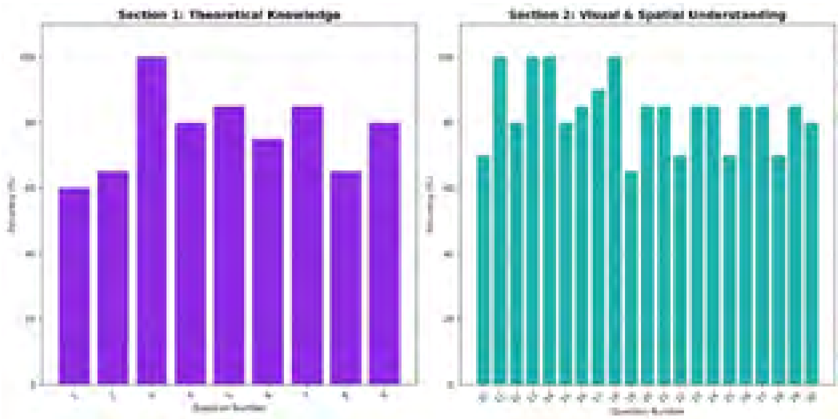

Figure 1: Game based, Part 1 and 2 Results - Theoretical Knowledge/Visual & Spatial Understanding

In contrast, the text-based group's responses showed greater variability, likely reflecting differences in individual focus and attention during reading. While this group achieved higher success rates in the theoretical questions, with most scores falling in the 70% to 90% range, their performance on the visual and spatial questions was much more inconsistent, with accuracy rates ranging from 40% to 100%. This variability suggests that, although some participants were able to use imagination or prior knowledge to answer spatial questions, others struggled without the benefit of interactive or visual exploration.

An interesting finding was that game-based participants performed well in theoretical questions, indicating that the game's context and visual cues may have reinforced theoretical learning. Conversely, some text-based participants achieved high scores in spatial questions, possibly by effectively visualizing and imagining the spatial concepts described in the text.

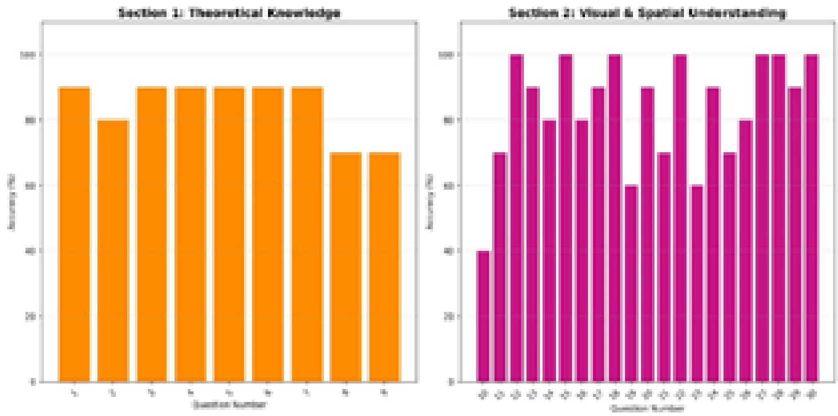

Figure 2: Text based, Part 1 and 2 Results - Theoretical Knowledge/Visual & Spatial Understanding

It is also likely that the interactive and enjoyable nature of the game-based learning environment contributed to higher engagement among participants, which may have supported more consistent and effective learning outcomes, particularly in the spatial section.

9. DISCUSSION AND CONCLUSION

The findings of this study provide important insights into the comparative effectiveness of game-based and text-based instructional methods in architectural education. The results demonstrate that while both approaches can facilitate the acquisition of theoretical knowledge, the game-based method offers distinct advantages in fostering spatial understanding and ensuring a more consistent distribution of learning outcomes among participants.

A key observation is the consistent and high performance of the game-based group in the visual and spatial comprehension section. The interactive and immersive nature of Assassin's Creed Odyssey's Discovery Mode enabled participants to actively engage with architectural environments, navigate spaces, and interact with features in real time. This hands-on experience appears to have supported the development of robust spatial cognition, as reflected in the group's high accuracy rates and balanced responses. The opportunity to pause, explore, and directly experience architectural elements contributed to a deeper and more uniform understanding of spatial relationships and visual details.

These interactive encounters, such as navigating courtyards, engaging with domestic and sacred spaces, and participating in social life, facilitated a form of learning that is active, contextual, and deeply immersive. This approach aligns with experiential learning theory and underscores the unique educational value of game-based environments in teaching complex architectural, cultural, and social concepts. Unlike video-based or text-based instruction, which confines the learner to a predetermined viewpoint and sequence, the interactive environment empowers users to explore, inquire, and engage with the content in a manner that is both personal and meaningful. The ability to interact, such as entering a space and conversing with characters, helps participants remember activities more vividly, as the act of participation reinforces memory retention.

In contrast, the text-based group, while achieving relatively high scores in theoretical questions, exhibited greater variability in the spatial section. This suggests that passive engagement with transcribed content, even when comprehensive and well-structured, may not be sufficient to support all learners equally in developing spatial understanding. The variability in performance may be attributed to differences in individual imagination, prior knowledge, or attention during reading, highlighting the limitations of traditional text-based instruction for spatially complex subject matter. The lack of agency and interaction in passive learning environments limits the depth of engagement and the potential for meaningful learning.

An unexpected but noteworthy finding is the strong performance of the game-based group in theoretical questions. This suggests that the contextual and visual cues embedded in the game environment not only enhance spatial learning but also reinforce the retention of factual and conceptual information. Conversely, the occasional high performance of text-based participants in spatial questions indicates that some individuals can construct mental models from text alone, though this is less consistent across the group.

The study also underscores the role of engagement in learning outcomes. The interactive, enjoyable, and exploratory qualities of the game-based environment likely contributed to sustained attention and motivation, which are critical factors in effective learning. This is particularly relevant in architectural education, where the ability to visualize and mentally manipulate spaces is essential.

In conclusion, the research highlights the potential of gamification and immersive virtual environments as powerful tools in architectural education. Game-based learning not only supports the acquisition of theoretical knowledge but, more importantly, provides a significant advantage in developing spatial understanding, a core competency in the field. While text-based methods remain valuable for conveying information, their limitations in supporting spatial cognition suggest that they are best used in conjunction with more interactive approaches. These findings have important implications for educators and curriculum designers, advocating for the integration of game-based and experiential learning strategies to enhance educational outcomes in architecture and related disciplines.

Future research could further explore the long-term retention of knowledge gained through game-based learning, the impact of different types of interactivities, and the applicability of these findings to other domains requiring spatial skills. Overall, this study contributes to the growing body of literature on gamification in education and demonstrates the unique value of virtual environments in bridging the gap between theoretical knowledge and real-world experience.

REFERENCES

Abdelhameed, W. (2013). Virtual reality use in architectural design studios: A case of studying structure and construction. Procedia Computer Science, 25, 220-230.

Champion, E. (2015). Critical Gaming: Interactive History and Virtual Heritage. Routledge.

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: Defining "gamification". MindTrek.

Gee, J. P. (2003). What Video Games Have to Teach Us About Learning and Literacy. Palgrave Macmillan.

Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? – A literature review of empirical studies. Hawaii International Conference on System Sciences.

Kolb, D. A. (1984). Experiential Learning: Experience as the Source of Learning and Development. Prentice Hall.

Maher, M. L., Simoff, S., & Cicognani, A. (2013). Understanding Virtual Design Studios. Springer.

Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research. Computers & Education, 56(3), 769-780.

Mortara, M., Catalano, C. E., Bellotti, F., Fiucci, G., Houry-Panchetti, M., Petridis, P., & Spagnolli, A. (2014). Learning cultural heritage by serious games. Journal of Cultural Heritage, 15(3), 318-325.

Salama, A. M. (2015). Spatial design education: New directions for pedagogy in architecture and beyond. Ashgate.

Saghafi, M. R., Franz, J., & Crowther, P. (2012). Perceptions of physical versus virtual design studio education. International Journal of Architectural Research, 6(1), 6-22.

Schön, D. A. (1983). The Reflective Practitioner: How Professionals Think in Action. Basic Books.

Appendix A: Survey Instrument

Section 1

1. What is the Parthenon primarily known for?
a) Its large dome
b) Its intricate carvings
c) Its underground chambers
d) Its use as a fortress

2. What was the Parthenon primarily built to symbolize?
a) The power of the gods
b) The glory of Athens
c) The wealth of Greece
d) The strength of democracy

3. What mythological event is depicted on the Parthenon's carvings?
a) The Trojan War
b) Athena's fight against Poseidon
c) The labors of Heracles
d) The fall of Troy

4. What was the purpose of the pool in the Parthenon's cella?
a) To store water for rituals
b) To control humidity for the room
c) To reflect light into the chamber
d) To cool the room during summer

5. Who founded the Stoic school of philosophy in the Painted Stoa?
a) Socrates
b) Plato
c) Zeno of Kition
d) Aristotle

6. What was the Bouleuterion used for?
a) Hosting symposia
b) Housing the council of citizens
c) Storing food
d) Holding religious ceremonies
7. What was the Heliaia?
a) A temple
b) A court of law
c) A marketplace
d) A school
8. What was the Greek term for the household?
a) Oikonomia
b) Andron
c) Gynaikonitis
d) Oikos
9. What was the term for the women's section of the house?
a) Andron
b) Gynaikonitis
c) Oikos
d) Pastas

Section 2
10. What material was used to create the statue of Athena in the Parthenon?
a) Marble
b) Bronze
c) Gold and ivory
d) Stone
11. What did Athena in Parthenon hold in her right hand?
a) A spear
b) A shield
c) A winged Nike
d) A laurel wreath
12. What was the agora primarily used for?
a) Religious ceremonies
b) Civic, commercial, and social activities
c) Military training
d) Agricultural storage
13. What was the Painted Stoa known for?
a) Its sculptures
b) Its panel paintings
c) Its large columns
d) Its marketplace
14. What architectural element was commonly found in the Agora to facilitate public gatherings?
a) Open spaces surrounded by stoas
b) Large domes for acoustics
c) Underground tunnels for storage
d) Elevated platforms for speeches

15. What was the central feature of a Greek house?
a) The kitchen
b) The courtyard
c) The andron
d) The gynaikon
16. What was the purpose of the courtyard in Greek houses?
a) To store food
b) To allow air circulation and provide light
c) To house livestock
d) To serve as a guest area
17. What material were Greek house floors typically made of?
a) Marble
b) Packed mud
c) Stone tiles
d) Wood
18. What was the andron used for?
a) Cooking
b) Hosting symposia
c) Storing food
d) Sleeping
19. What was a pastas in a Greek house?
a) A corridor connecting the courtyard to the residential section
b) A storage room for food
c) A room for women's activities
d) A guest room
20. What was often located in the center of the courtyard?
a) A well or cistern
b) A dining table
c) A fireplace
d) A storage chest
21. What was the Greek diet primarily based on?
a) Meat and fish
b) Grains, grapes, and olives
c) Dairy products
d) Exotic spices
22. What was the purpose of a louterion in the bathroom?
a) To store perfumes
b) To hold water for washing
c) To heat the room
d) To grind grains
23. What was the symposium?
a) A religious ceremony
b) A men's drinking party
c) A women's gathering
d) A political meeting
24. What furniture was used in the andron during symposia?
a) Klinai (couches)
b) Folding stools
c) High chairs
d) Benches

25. What was the purpose of the altar in the courtyard?
a) To honor Zeus Herkeios
b) To store food
c) To provide light
d) To mark the entrance

26. Where was the bathroom typically located in a Greek house?
a) Near the courtyard
b) In the back of the house
c) On the upper floor
d) Next to the kitchen

27. What did the Greeks use instead of toilets in their bathrooms?
a) Wells
b) Chamber pots
c) Clay basins
d) Wooden buckets

28. Which of the following items could be found in a Greek bathroom?
a) Mirrors, razors, and sponges
b) Cooking pots and utensils
c) Lamps and candles
d) Writing tools and scrolls

GENERATIVE AI WORKFLOWS: EXPLORING STRATEGIES FOR BALANCING AI CREATIVITY AND DESIGNER INTENT

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ABSTRACT:

Generative AI has transformed the early stages of design by enabling creation of complex visuals that are especially useful when clarifying project briefs and objectives. While it is relatively straightforward to generate a wide range of solutions, the challenge lies in systematically guiding the design process, making precise adjustments, and maintaining control over design iterations. This research addresses these challenges by exploring intuitive workflows that empower designers to steer AI-generated outputs effectively.

This paper presents an experiment focused on understanding how relatively inexperienced users can utilize one of the available generative AI tools (OpenArt.ai was chosen for comprehensiveness and feature richness) to conduct a design interview and guide the generative AI. Students from first and second grade of architecture school were briefly introduced to the chosen tool prior to the experiment. In order to map design steering progression, the user-centric principles were implemented into our experiment methodology, including a structured role-playing approach between "designer" and "user" roles. This methodology allowed for iterative feedback collection and analysis across up to four distinct design iterations. Each iteration's inputs and outputs were meticulously documented with visuals, prompts, user requirement descriptions, sketches, scores and evaluations.

The findings reveal that while AI facilitates the generation of diverse ideas, maintaining precise control over iterative design processes is more complex than anticipated. The experiment confirmed the need for tailored workflows, targeted training, and a nuanced understanding of AI functionalities (e.g., inpainting, image guidance parameters, and prompt adherence). By analyzing successful workflows in detail across iterations, we identify strategies to enhance the alignment of AI outputs with design intent. This paper also provides an analysis of common errors that may hinder effective design steering, offering valuable insights for improving design processes.

Keywords: design intent, user-centric design, prompt engineering, user experience with AI, sketch to image, steering AI output,

INTRODUCTION

Generative AI has rapidly become a transformative force in the early stages of design, enabling the rapid production of rich, complex visuals from simple textual input. These capabilities are especially valuable in the conceptual phase of projects, where designers seek to explore options, clarify briefs, and align on user needs as already explored by Li, Li and

Li, (2024). However, despite the ease of generating diverse ideas, designers often struggle with guiding the process in a controlled and purposeful way—especially when trying to maintain coherence across multiple iterations. As stated by Yuan (2023): "AI is gradually demonstrating analytical ability and creativity, bringing vital "vision" to humanity."

This study investigates how beginner-level design students engage with a generative AI tool to steer design outputs in response to user needs. Rather than focusing solely on the generative power of AI, our research emphasizes the process of design steering: how users interact with the tool to refine, redirect, and align AI-generated content with specific design objectives. As observed by Li *et al.*, (2024), there are still workflow integration gaps, despite the amount of tools and AI architectures available even to such a field as architecture and design. In spite of the aforementioned research, our experiment is focusing on a structured, role-playing methodology, where students alternate between the roles of "designer" and "user." This setup not only simulates real-world design communication (and therefore usability) but also makes it possible to systematically evaluate how well participants can extract meaningful results from the AI tool.

By observing students as they iteratively guided a commercially available AI sketching platform (OpenArt.ai), we assess how intuitive their chosen workflow was, what kinds of results were achieved, and which aspects of the process posed the greatest challenges. To facilitate a frictionless environment for the experiment participants to work in, we've chosen the platform OpenArt.ai. The main features required to fit our criteria of choice were feature richness (especially tools like inpainting and sketch-to-image), comprehensive UI for novice users (ComfyUI requires significant amount of terminology being known prior to confident usage for example) and enough freedom to use the platform in evaluation period to be able to accommodate 3 - 4 design iterations. Our goal is to better understand the interplay between human designer intent and AI behavior.

This research contributes to a growing body of work that moves beyond the novelty of AI-generated imagery and toward more effective, designer-led workflows. Through this lens, we aim to highlight both the opportunities and limitations of generative tools, and to propose practical strategies for enhancing human–AI co-creation in design education and practice.

METHOD

In order to be able to evaluate partial results and successfulness of different design interactions, we developed a user-centered roleplaying design method and a protocol to record design dialogues in their iterations between role-played *user* and *designer.* As the *user* gradually adds more details and requirements through the design process, the *designer* is motivated to accommodate the needs of the *user* and therefore make the *user's* score increase as illustrated in Figure 1. In such a context the score is important to evaluate whether the *designer* is successful in fulfilling the *user's* needs - therefore able to steer the AI generative tool according to his design intentions. This can be compared to similar methods used in other fields spanning from linguistics to military research and broadly classified as human-in-the-loop approach. The current focus on usability and utility of AI-assisted tools was also explored by Ranade, Saravia and Johri (2024) such as GPT-3, are a particular concern for professionals engaged in writing, particularly as their engagement with these technologies is limited due to lack of ability to control their output. Most efforts to maximize and control output rely on a process known as prompt engineering, the construction and modification of the inputted prompt with expectation for certain outputted or desired text. Consequently, prompt engineering has emerged as an important consideration for research and practice. Previous conceptions of prompt engineering have largely focused on technical and logistic modifications to the back-end processing, remaining inaccessible and, still, limited for most users. In this paper, we look to the technical communication field and its methods of text generation—the rhetorical situation—to conceptualize prompt engineering in a more comprehensible way for its users by considering the context and rhetoric. We introduce a framework, consisting of a formula, to prompt engineering, which demands all components of the rhetorical situation be present in the inputted prompt. We present discussions on the future of AI writing models and their use in both professional and educational settings. Ultimately, this discussion and its findings aim to provide a means of integrating agency and writer-centric methods to AI writing tools to advance a more human-in-the-loop approach. As the use of generative AI and especially NLP-based technologies become common across societal functions, the use of prompt engineering will play a crucial role not just in adoption of the technology, but also its productive and responsible use.","container-title":"AI & SOCIETY","DOI":"10.1007/s00146-024-01905-3","ISSN":"1435-5655","issue":"2","language":"En","license":"2024 The Author(s.

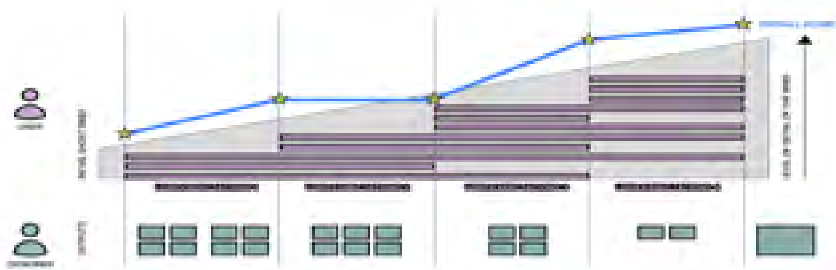

Figure 1: Increasing level of detail and amount of information about *user's* requirements forces the *designer* to react accordingly and steer the AI generation towards fulfilling the requirement. This when coupled with detailed scoring can provide insights into the successfulness of the design interview.

Two questionnaires were conducted, one before the experiment and another one immediately after the experiment just before any discussions and overall feedback session started in order to gather raw impressions without participants being affected by hearing opinions of other participants. A short introduction into the problematic of AI generated images in design was held prior to the experiment day and participants had time to test different AI tools like sketch-to-image and inpainting in order to be able to use them intuitively during the experiment.

DESIGN STEERING PROTOCOL DESCRIPTION

The design steering protocol developed for this study serves as a structured framework to capture and evaluate the iterative collaboration between a *designer* and a *user*, where the *designer* uses a generative AI tool. The protocol starts with a DESIGN BRIEF section and is then divided into clear, repeatable vertical sections that allow for systematic documentation of INPUTS, OUTPUTS, and SCORE across multiple *Design iterations*.

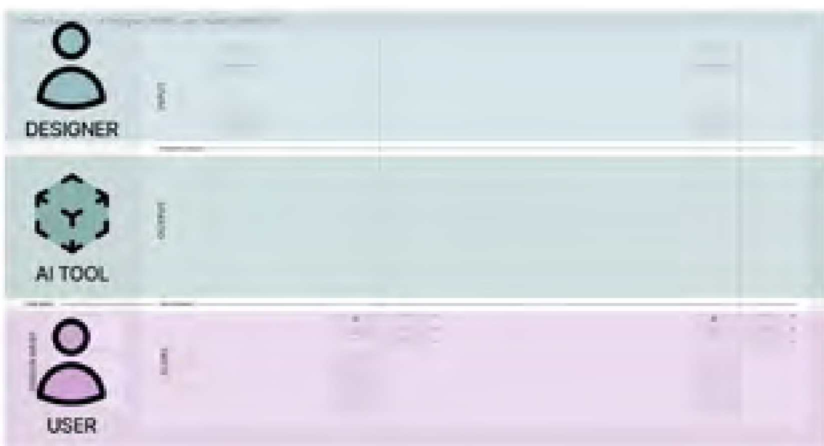

Figure 2: Horizontal sections for the *designer's* INPUTS, AI tool's OUTPUT and *user's* SCORE

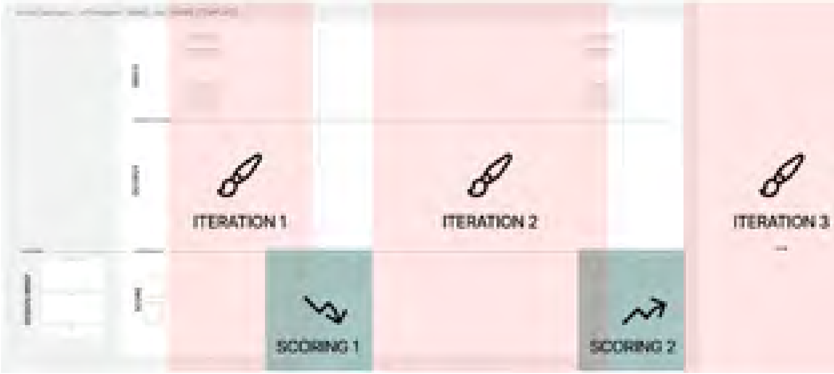

Figure 3: Vertical sections for each *Design Iteration*

USER'S SCORING DESCRIPTION

Each *Design Iteration* includes a structured feedback area where the *user* evaluates the proposed designs. This includes a numerical overall design score (scale from 0 to 10) and qualitative textual comments assessing aspects such as material use, shape accuracy, and the degree of alignment with user expectations. This feedback can be voluntarily enhanced by a *user's* sketch providing extra information usually about shapes and forms which would be otherwise quite difficult to express in a text. Additionally, the protocol also enables the *user* to express their opinion in the OUTPUT section by directly placing a green frame over the part of a generated output which is desired and a red frame to express dislike of certain image parts or features. And lastly the *user* should also express three EXPECTATIONS for the next *Design Iteration.* These EXPECTATIONS are then scored as well numerically (scale from 0 to 10) at the end of the next *Design Iteration.* This way the *designer* is provided with a multitude of information to act upon in the next *Design Iteration.*

EXPERIMENT METADATA

The preliminary group of participants included 14 students who formed 7 designer-user pairs. In reaction to recent research conducted by Kulkarni *et al.* (2023), we initially look for qualitative data and participant satisfaction in order to later move towards a more quantitative approach once we have a better understanding of the struggles participants might be facing. Therefore a short survey was conducted before the experiment and also after it. The pre-study questionnaire revealed that a large majority of participants considers themselves novices or unskilled with AI image generators with only one participant reporting a score of more than 5 on a scale from 0 to 10 in the self-evaluation of prior skills. Furthermore only 4 participants reported no prior experience with any of the image generators, others already used some of them before the experiment.

The post-study questionnaire revealed a highly positive evaluation of perceived usability and usefulness of AI tools in the context of user--centered ideation - the average score was 7.91 on a scale from 0 to 10. Another surprising outcome was that almost all the participants felt very comfortable with role switching between iterations - the average score was even 8.00 on a scale from 0 to 10, no one submitted a score lower than 5.

DISCUSSION

One example of the protocol data gathered during the experiment is depicted in Figure 4 and 5. Initially the authors expected some insights from learning how many different tools were used and in which order, however the small preliminary sample size did not yield enough data to draw conclusions with significance.

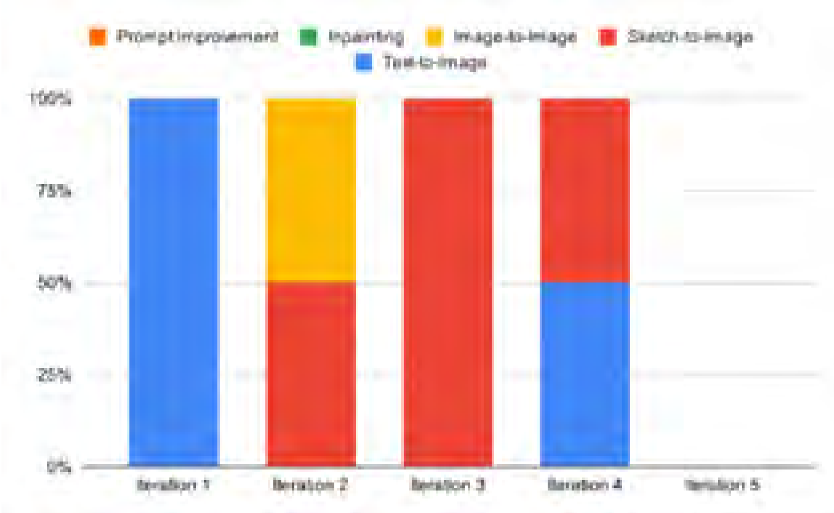

Figure 4: AI tools used in each *Design Iteration* by one participant

On the other hand, the information about design fluency as defined by Wadinambiarachchi *et al.*, (2024) sparked our interest while paired with the overall score of each design iteration. Eventually we gathered all the quantitative data into one graph to observe trends throughout the design iterations. As Figure 5 shows, the number of images generated lowers with higher scores towards the end of the experiment as well as the number of evaluation frames (Red frames for negative and Green frames for positive evaluation).

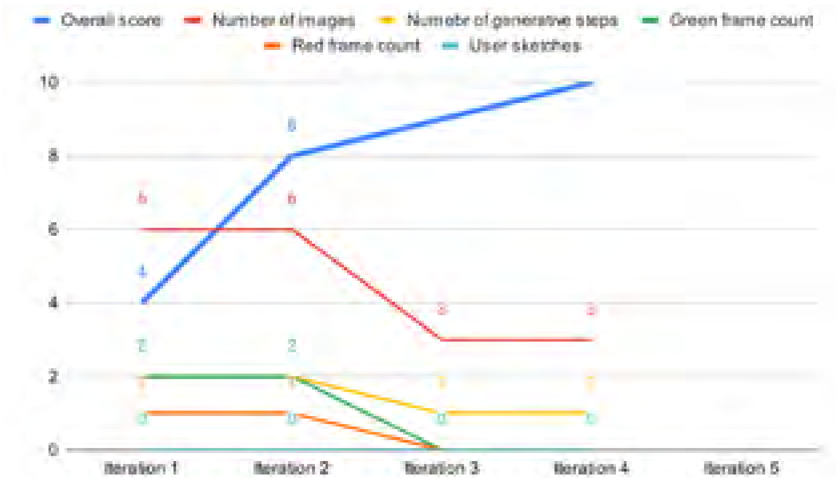

Figure 5: As the *Overall score* grows higher in each successive *Design Iteration* of one Designer, the amount of feedback methods lowers.

The overall score gradually increased in all pairs with only one exception. In such a small sample size it is not uncommon, however we could speculate whether some kind of social pressure to be kind to your mate didn't play a role to obscure a proper design improvement. This would be better observed on a larger sample size - which is planned in the immediate future.

Conclusion

This study demonstrates that while generative AI tools like OpenArt.ai provide immense potential for creative exploration in early design phases, steering these tools toward meaningful, user-aligned outcomes remains a nuanced challenge—especially for novice designers. Our experiment revealed that although participants could generate diverse visual outcomes quickly, many struggled with maintaining control across design iterations, often encountering moments of frustration or even design fixation. This highlights a central tension in AI-assisted design: the ease of visual generation can obscure the difficulty of intentional iteration.

The role-playing protocol we developed provided an effective framework for simulating real-world design dialogue, pushing students to refine their ideas and articulate them more clearly with each iteration. The scoring and feedback mechanism, including user sketches and visual framing, offered actionable insights and fostered a richer understanding of user needs. However, the added cognitive load of protocol documentation—especially under time constraints—sometimes disrupted participants' creative flow, leading to incomplete data records or skipped steps.

KEY FINDINGS

A majority of participants exhibited an upward trajectory in their overall scores. On average, **design scores increased by 1.7 points** from the first to the final iteration, demonstrating an improvement in aligning AI outputs with user intent over time. However, some groups plateaued or even regressed in later iterations, often due to unclear feedback loops or design fixation.

Participants utilized between **1 and 5 distinct AI tool functionalities** across their workflows. The most frequently used tools were **text-to-image** and **sketch-to-image**, followed by **image-to-image** inputs. Notably, groups that used **at least three distinct tool functionalities** achieved, on average, a **14% higher final score** compared to those who used only one or two. This suggests that a more nuanced use of available generative features correlates with improved outcomes—though not in a strictly linear fashion.

Protocol analysis revealed that the number of **explicit generative steps** (defined as recorded prompt modifications, sketch applications, or inpainting adjustments) ranged from **3 to 14 per participant**, with an average of **8.2 steps**. However, a higher number of steps did not always correlate with higher scores; in some cases, overproduction without strategic refinement led to decreased performance, highlighting the risk of quantity over quality.

While the structured protocol enabled precise mapping of design decisions, it also introduced friction. Several participants reported that documenting inputs and outputs during the creative flow was intrusive, and in a few instances, **protocol entries were skipped or retroactively filled**. This points to a key trade-off: the value of granular documentation for research purposes vs. the cognitive overhead it places on novice designers during creative tasks.

WORKFLOW OBSERVATIONS

Successful participants typically exhibited the following behaviors:

- Clear re-interpretation of user feedback into actionable AI prompts
- Layered use of tools (e.g., using inpainting *after* image generation to refine specific regions)
- Gradual visual convergence across iterations, rather than radical reboots
- Use of user sketches or color frames to guide iterative adjustments

Conversely, participants who struggled often displayed:

- Literal or overly simplistic interpretation of user expectations
- Repetition of the same prompt with minimal variation
- Lack of attention to iterative feedback or expectation scoring
- Over-reliance on a single tool (e.g., only prompt modification in text-to-image)

These findings emphasize the importance of structured workflows, intuitive tool interfaces, and better onboarding strategies when integrating generative AI into design education. Rather than focusing solely on tool features, the key to successful outcomes lies in cultivating a designer's ability to interpret feedback, manage iteration cycles, and understand the AI's generative logic. Future design education should therefore include not only technical training, but also protocols for reflective design dialogue and critical evaluation of AI outputs.

Ultimately, we argue that meaningful human–AI collaboration in design is not achieved by simply generating more images or using more features, but by learning how to think with the tool—strategically, iteratively, and critically. In conclusion, generative AI does not replace the need for structured design thinking; rather, it amplifies the importance of intentional, feedback-driven iteration. This might sound in contrast to the frameworks developed by Bagasi, Nawari and Alsaffar (2025), however our work is focusing on a more low level type of AI tool integration where the designer still has to manage the entire project and doesn't need assistance from AI on the level of Only when designers learn to steer AI creatively and critically can human–AI collaboration move from novelty to professional utility in architectural design.

FUTURE WORK

Our findings suggest that effective steering of generative AI is less about mastering a single feature and more about developing a workflow literacy - the ability to make sense of feedback, adapt tool usage dynamically, and iterate with purpose. While the AI offers expansive visual possibilities, the designer's role remains critical in shaping coherence, progression, and alignment with user goals.

Future experiments should invite a significantly larger group of participants and could explore longer design sessions, compare novice vs. expert behavior, and assess alternative locally run platforms (e.g., ComfyUI or Krita). A promising direction could be using ComfyUI which enables logging the entire workflow with its metadata, reducing the manual overhead of protocol-based documentation while preserving traceability of the design process. Thus, removing the friction on the experiment participants as well as data processing after the workshop.

REFERENCES

Bagasi, O., Nawari, N.O. and Alsaffar, A. (2025) 'BIM and AI in Early Design Stage: Advancing Architect–Client Communication', *Buildings*, 15(12), p. 1977. Available at: https://doi.org/10.3390/buildings15121977.

Kulkarni, C. *et al.* (2023) 'A Word is Worth a Thousand Pictures: Prompts as AI Design Material'. arXiv. Available at: https://doi.org/10.48550/ARXIV.2303.12647.

Li, C. *et al.* (2024) 'Generative AI Models for Different Steps in Architectural Design: A Literature Review'. arXiv. Available at: https://doi.org/10.48550/ARXIV.2404.01335.

Li, P., Li, B. and Li, Z. (2024) 'Sketch-to-Architecture: Generative AI-aided Architectural Design'. arXiv. Available at: https://doi.org/10.48550/arXiv.2403.20186.

Ranade, N., Saravia, M. and Johri, A. (2024) 'Using rhetorical strategies to design prompts: a human-in-the-loop approach to make AI useful', *AI & SOCIETY*, 40(2), pp. 711–732. Available at: https://doi.org/10.1007/s00146-024-01905-3.

Wadinambiarachchi, S. *et al.* (2024) 'The Effects of Generative AI on Design Fixation and Divergent Thinking', in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery (CHI '24), pp. 1–18. Available at: https://doi.org/10.1145/3613904.3642919.

Yuan, P.F. (2023) 'Toward a generative AI-augmented design era', *Architectural Intelligence*, 2(1), pp. 1–3. Available at: https://doi.org/10.1007/s44223-023-00038-9.

OPTIMIZATION OF 3D OBJECTS FOR ARCHITECTURAL VISUALIZATION IN VR

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ABSTRACT:

Virtual reality is an important tool for architects, allowing them to present the future object to the client from the early stages of design. A scene in virtual reality can be presented in two ways: by a VR headset connected to a computer or in standalone mode. With high-quality optimization, standalone VR systems can demonstrate graphics that are not inferior to VR devices connected to a computer, while remaining mobile, allowing the architect to flexibly organize meetings with the client. An effective scene optimization system is also necessary for stable and high FPS, which directly affects the comfort of the user experience and immersion in VR.

Since models for architectural visualization are often not intended for use in VR, optimization of their geometry is necessary. Using manual optimization gives more control over preserving the visual quality of a 3D

object and does not violate the UV-map structure, unlike the automatic optimization method. Creating retopology and using normal maps allows to preserve the level of detail of objects without increasing the number of polygons and thus reducing the load on the graphics card.

The experimental part of this work examines in detail the effect of scene optimization on its performance. As part of the study, 2 scenes were created: the first included 3D models of interior elements downloaded from archviz sites, and the second - their optimized versions created as part of this work.

In the next step, the performance of both scenes is analyzed and the impact of 3D object optimization on the overall efficiency of the scene is assessed.

The ability to work with optimization allows the architect-visualizer to create high-quality realistic projects that enable the future structure to be presented favorably and increases efficiency in working with the customer.

Keywords: Architectural visualization, virtual reality, scene optimization, geometry optimization, mesh, retopology

1. INTRODUCTION: VR – AN EFFECTIVE TOOL FOR ARCHITECTURAL DESIGN

Architectural visualization is an integral part of design work, since already at the early stages it allows the future structure to be clearly demonstrated to the customer. Thanks to the rapid development of technology, the quality of architectural rendering has reached such a high level that it is often difficult to distinguish the visualization of an object from a real photograph. Until recently, the demonstration of such realistic images was one of the main methods of presenting a future architectural object to the customer in a favorable light.

The advent of VR technologies has given architects another effective tool for interacting with the client. Architects-visualizers have begun to increasingly integrate the use of virtual reality into their work, which has significantly increased productivity at all stages of design process.

If render images allowed the customer to see the object from a limited number of angles, the use of VR opened up a new opportunity - full immersion into the architectural space and the creation of the effect of presence inside the designed object. The customer can "walk" through the object in real time, feel the created environment of space better and make the necessary changes already at the early stages of design. This allows timely detection and prevention of possible errors, reduction of project implementation time and minimization of unnecessary labor costs during construction work.

The use of VR facilitates communication between the architect and the client, which makes the collaboration process more effective. It is especially crucial to use VR at the project presentation stage, during which it is important not only to convey the architectural idea, but also to create a holistic spatial perception of the future object in the client using the presence effect.

2. EQUIPMENT VARIANTS FOR WORKING WITH VR

There are two main options for presenting a scene in virtual reality: with a headset connected to a computer (tethered) and without a connection (standalone).

When using a VR headset connected to a computer, not only the headset and controllers are required, but also expensive computer equipment is needed. In this case, meetings with the client usually take place directly in the architectural office, where all the necessary equipment is located.

The option that does not require connecting the helmet to the computer only requires the presence of a headset and controllers, which significantly reduces costs of equipment and increases the mobility of the work process. The architect gets the opportunity to plan meetings with the client more flexibly, not limiting them to only being held on the architect's office premises.

The choice of equipment for working with virtual reality is determined by the project features and individual requirements (creative and technical tasks) of the architect. With high-quality scene optimization, including work with 3D models, lighting and other scene parameters, standalone VR systems can demonstrate graphics that are not inferior in visualization quality to VR devices that require a connection to a computer. Implementing the scene optimization process at the early stages of project development allows to reduce equipment requirements, reduce production costs and increase mobility when presenting the project to the customer.

3. FRAMES PER SECOND

Regardless of the type of VR equipment chosen for work, tethered or standalone, both options require a VR headset that allows the user to move freely around the virtual scene and independently change the viewing angle.

Because the camera in VR responds to the user's movements in real time, the scene's image display is rendered tens of times per second. The number of frames of rendered images displayed in one second is called the frame rate (FPS).

To form an image in a VR helmet, a separate virtual camera is used for each eye, which creates a stereoscopic effect and enhances the feeling of presence. However, using two cameras significantly increases the load on the system, since each scene must be rendered twice. This effectively doubles the required number of frames per second when using VR.

To ensure stable and comfortable visual perception in a virtual reality environment, the minimum acceptable frame rate is considered to be 90 FPS. The optimal value, providing maximum realism and reducing the load on the user's vestibular apparatus, is around 120 FPS. For comparison, when developing computer games that do not involve the use of VR, the standard is considered to be 30 or 60 FPS. Thus, creating high--quality VR experience requires significantly higher performance of the system, especially from the graphics processor.

A stable and high frame rate (FPS) is very important when working with virtual reality, as it directly affects the quality of the user experience and the level of immersion. To achieve such a high level of performance, a well-thought-out and high-quality implemented scene optimization system is necessary. It is important to determine at an early stage of design that the project is being developed taking into account the requirements of VR, as this will avoid reworking later and increase the efficiency of the development process.

4. VR SCENE OPTIMIZATION

In this chapter, some of the main ways to optimize a scene for work with VR are explored.

4.1. Geometry optimization

4.1.1. Automatic optimization of model geometry

Automatic model optimization is the process of simplifying the polygonal mesh of a 3D model using software tools aimed at reducing the number of polygons while maintaining the appearance of the model.

When using automatic optimization of a model, it is important to consider that along with the simplification of geometry, its topology also changes. The topology of a 3D object is the structure and organization of the polygonal mesh of the model, including the location and mutual relationship of vertices, edges and polygons. The efficiency of optimization and the level of visual quality of the object in the engine depend on the quality of the topology. One of the main principles of creating high-quality topology is that the polygonal mesh should mainly consist of quadrangles, close to a square shape, evenly distributed over the surface of the object. Automatic optimization often leads to the formation of elongated and uneven polygons, which can negatively affect the quality of shading and, as a result, the appearance of the model.

Changing the topology with the automatic optimization method also affects the UV map of the model. UV mapping is the translation of the 3D model surfaces onto a two-dimensional plane for subsequent texture application. Deleting or shifting vertices disrupts the structure of the existing UV map, which leads to distortion of the texture mapping. In such cases, the developer has to re-create the UV map to restore the correct mapping of textures. If there are previously baked unique textures, it is necessary to completely recreate them, including re-painting and baking.

Automatic optimization is most often used for static objects in LOD (Level of Detail) systems, where objects located far from the camera are replaced with simplified models with less detail that preserve their overall silhouette.

Automatic optimization – 687 vertices

Original model

Manual optimization – 680 vertices

Figure 1: Example of automatic optimization of model geometry

4.1.2. Manual optimization of model geometry

Manual model optimization is the process of manually editing a polygonal mesh to reduce the number of polygons, improve topology, and remove unnecessary geometry while maintaining the visual characteristics of the object.

Manual optimization can be used both for editing existing geometry and for creating retopology based on a highly detailed model. Retopology is the process of re-creating a polygonal mesh of a 3D model with a simplified and optimal topology, ensuring efficient rendering and ease of further work with the model, while maintaining the shape and visual features of the original highly detailed model.

Removing invisible polygons is one of the stages of manual optimization of a 3D model, aimed at reducing the number of polygons that do not affect the visual perception of the object. When optimizing a model, it is necessary to leave only visible surfaces, since polygons hidden from the user's view (for example, located on the back of the object or adjacent to other surfaces) do not affect the final display quality and can be removed to improve performance.

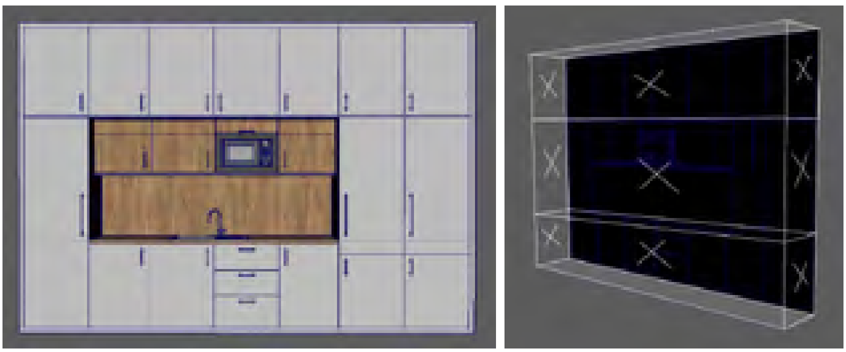

Figure 2: Example of deletion of polygons hidden from the user's view

4.2. Using normal texture

A normal texture is a map that adds detail to a 3D object without increasing the polygon count. Baking a normal map is the process of transferring surface details from a high-poly model to a low-poly model as a texture that simulates complex geometry.

High-poly – a model with a high level of detail, containing all the necessary geometric details

Low-poly – an optimized model with a low polygon number, preserving the general shape and silhouette of the object

Using normal maps allows to visually convey the high detail of the model while maintaining its low polygonality, which is especially important for real-time graphics used in VR.

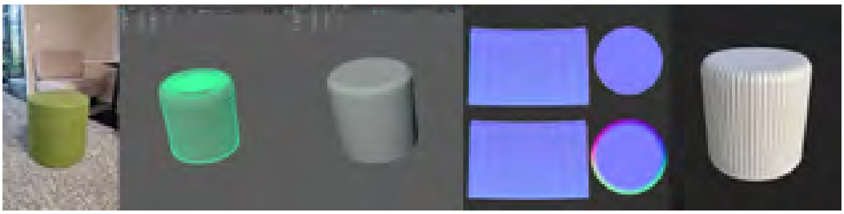

Figure 3: Example of normal map use

4.3. Optimization of materials

A material in 3D graphics includes a shader and textures that together form the appearance of an object. Effective optimization of materials requires attention to both the shader logic and the texture parameters.

Shader optimization is the simplification of its computational logic aimed at reducing the load on the graphics processing unit (GPU).

Texture optimization is a reduction in texture resolution, the use of texture compression (the texture takes up less space while maintaining image quality), the use of texture atlases (contains many subtextures in 1 image, used by 1 material)

Effective material optimization plays an important role in improving scene performance, reducing GPU load, and ensuring stable FPS.

4.4. Optimization of lighting. Shades

Lighting in 3D scenes can be static, dynamic and semi-dynamic. When optimizing a scene, it is recommended to use static light, which is baked into textures in advance and, unlike dynamic light, is not updated in real time, which minimizes the load on the system. This method is especially effective for static objects and scenes with stationary lighting, allowing to achieve realistic scene graphics with optimal system performance.

The choice of shadow type also significantly affects the performance of the scene. Soft shadows create a more realistic and smooth transition between light and shadow but require significantly more computing resources. To optimize and improve the efficiency of the scene, it is recommended to use hard shadows, which require fewer resources, but have sharper and clearer contours.

4.5. Optimization of reflections

Optimization of reflections in a 3D scene can be done using pre-calculated fake reflections (for example environment maps), reducing the resolution of reflections or limiting the number of reflective objects. These techniques help to significantly reduce the load on the graphics system, while maintaining visual quality and ensuring stable operation of the scene.

4.6. Grouping geometry elements into one object. Draw calls

A large number of sub-objects and materials in a scene increases the number of operations performed by the engine, which can lead to a decrease in FPS. One combined object is processed as one operation, which allows to significantly reduce the load on the system.

Draw calls are commands that the engine sends to the graphics processing unit (GPU) to display objects. Each individual object or unique material can create an additional draw call. Therefore, reducing the number of draw calls is an important step in scene optimization, especially in projects that require high performance in real time.

Working with object duplicates. Instancing

Instancing is an optimization method where a single 3D model is used multiple times in a scene without duplicating its geometry in memory, which significantly reduces the load on the graphics processor. This increases the overall efficiency of the scene, especially in projects with a large number of repeating objects.

4.8. Other optimization methods worth mentioning

Optimization methods are selected taking into account the specifics of the project and individual tasks set before the architect. Important techniques that affect scene performance also include:

- Using LOD (Level of Detail) technology - replacing scene objects with less detailed versions as they move away from the camera.
- Mipmapping – replacing original textures with their lower-resolution versions as the object moves away from the camera.
- Culling. Frustum Culling – excluding objects from rendering that are outside the camera's field of view. Occlusion Culling – excluding objects hidden by other objects (for example, behind walls) from rendering, even if they are within the field of view.
- Disabling or simplifying effects when working with post-processing, etc.

All of the abovementioned methods of optimization can significantly increase scene performance and ensure stable FPS, which is especially important for VR and real-time projects.

5. VARIANTS OF 3D MODELS OF REAL INTERIOR OBJECTS

As part of the experimental part of the author‘s doctoral work, one of the tasks was to create a digital twin of a real office in Prague. To work on this task, the interior objects were divided into 2 groups.

Group 1 included objects of simple geometry consisting of primitive forms. For example, tables and cabinets. This group of objects was modeled by the author herself.

Group 2 included objects with more complex, organic forms. For example, sofas or chairs with smooth geometry. This type of objects was downloaded from various sources on the Internet.

Figure 4 below shows 3D objects from the 2nd group, indicating the number of vertices used in the models and the sources from which these models were downloaded.

The search for a 3D model of a piece of furniture was made in Google with geolocation set in Czechia. The request was inputted in English (name of the piece of furniture + company + "3D model"). The first 2-3 pages of the search engine results were examined. Additionally, to search for 3D models, 2 websites for interior visualization (3ddd, cgkit) were used. On the websites the models were available in different formats (.max, .3ds, .dwg, .obj, .dxf, .skp and others), taking this into account, each model was converted to .fbx (universal format for all 3D programs), using the softest settings possible in order to not damage the original model, the original topology of each model remained in its original version.

Since the downloaded models contained an excessive number of vertices and were not adapted for use in VR, there was a need to optimize them. The conducted tests of automatic optimization (in Maya, ZBrush and Blender software) showed distortions of geometry and violation of the UV-map structure, in connection with which it was decided to perform manual optimization. The final optimized versions of the models and their characteristics are shown in the last column of the figure below.

Photo | Furniture Manufacturer | Furniture Dealers | Architectural Visualization | Optimized Model

Figure 4: Comparison of downloaded models and their optimized variants

Some models from the 2nd group of objects had an increased level of detail. To translate the level of detail, a normal texture was used, which was baked from a high-poly model downloaded from the Arch Visualization website onto a low-poly model created using manual optimization.

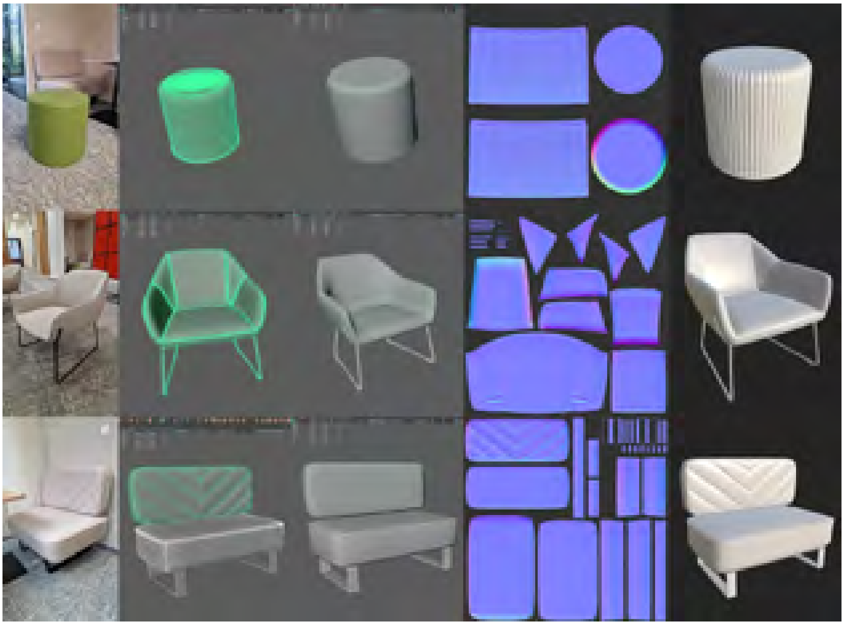

Figure 5: Optimization of high-poly objects using normal map

In the next stage of the experiment, 2 scenes were created: *the first* included 3D models intended for architectural visualization, *the second* their optimized versions created by the author within the framework of this work. As a result of comparing the performance of these scenes, an increase in FPS from 45 to 168 was observed, which clearly demonstrated the impact of optimization on system performance.

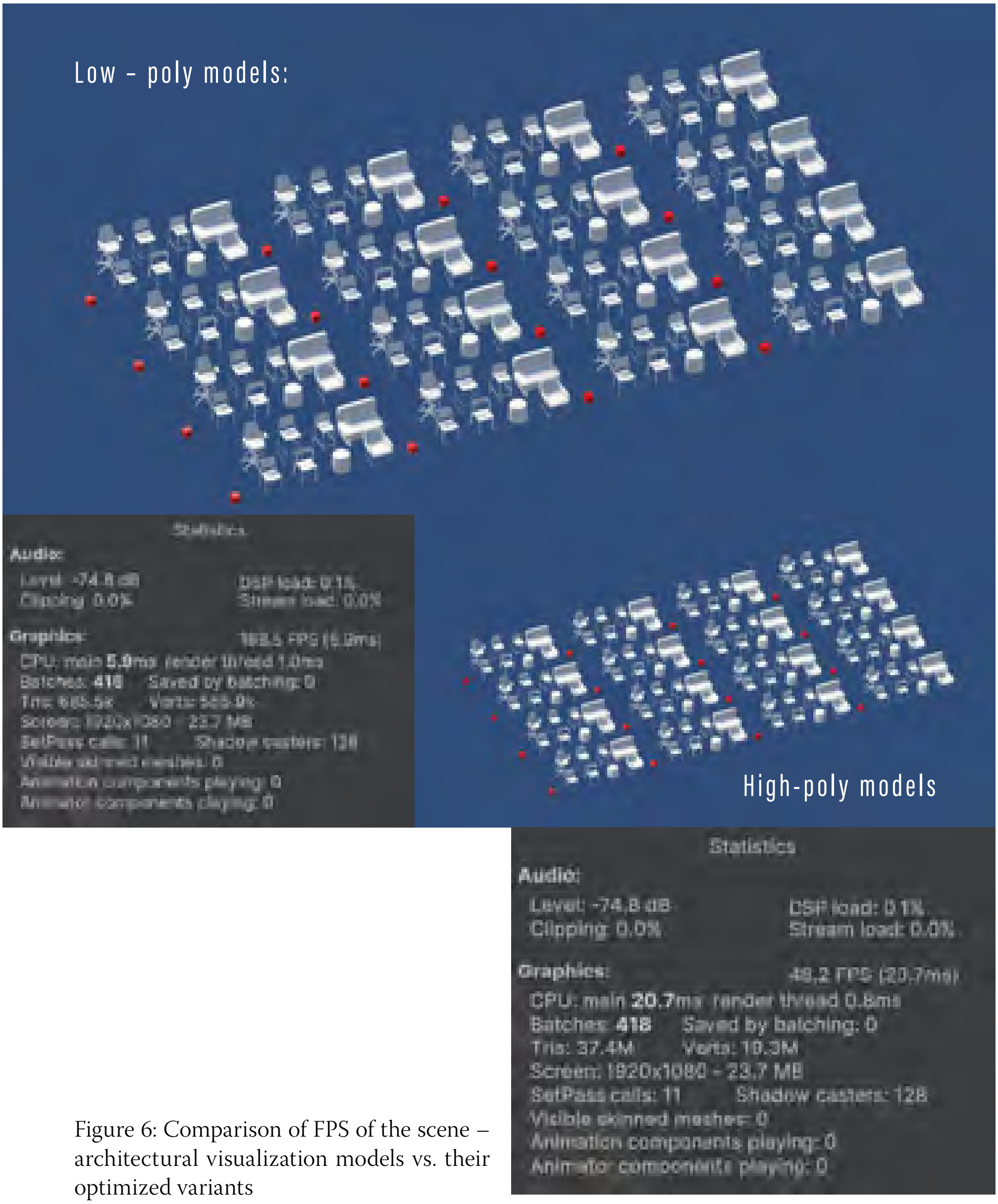

Figure 6: Comparison of FPS of the scene – architectural visualization models vs. their optimized variants

6. CONCLUSION

Virtual reality is an effective tool for an architect to interact with a customer, allowing for timely detection of possible errors, acceleration of the project implementation process and reduction of unnecessary labor costs at the construction stage. To ensure comfortable user experience in VR, a stable and high FPS is required, which is achieved with high-quality work with scene optimization.

In order to test the efficiency of optimization, an experiment was conducted within the framework of this paper. For the experiment, 3D models of interior elements downloaded from archviz sites were used. The analysis showed that these models contain an excessive number of vertices, their polygonal mesh has a high density and was not adapted for use in virtual reality scenes. Also, during a series of tests, it turned out that automatic optimization deforms the geometry of the models and disrupts the structure of the UV map, which served as the reason for using manual optimization. To create simplified versions of the models, retopology methods and the use of normal maps were used.

In the next stage of the experiment, 2 scenes were created: the first included original, non-adapted models of interior elements downloaded from archviz sites, and the second - their optimized versions created by the author as part of this paper. As a result of tests of the performance of the scenes, an increase in FPS from 48 to 168 was recorded, which clearly demonstrates the effectiveness of using model optimization when working with real-time graphics.

The results of the experiment showed that models intended for architectural visualization are not initially adapted for use in a virtual environment and require manual geometry optimization. The use of this method allows to control the topology of the object and its UV-maps, which directly affects the achievement of the required level of detail of the object without excessive load on the system. High-quality optimization ensures a balance between visual quality and technical efficiency, which is especially important for projects implemented in a virtual reality environment.

REFERENCES AND USED LITERATURE

Abuelainin, H. (2025) "Developing a Framework for Creating Virtual Reality (VR) in Architecture and Interior Design Processes", [online], University of Bahrain, https://journals.e-palli.com/home/index.php/jir/article/view/4390?utm

Xiaoyun, H. (2023) "Application of VR Technology in Interior Design", [online], Jiangxi Polytechnic of Industry and Trade, https://www.researchgate.net/publication/372118559_Application_of_VR_Technology_in_Interior_Design

Elbadawy, H. and Farouk, A. (2025) "Implementation of Virtual Reality Technology in Architecture Field, and Education: A Review", [online], https://link.springer.com/article/10.1007/s11831-025-10225-8

Pengjun, W., Yao, L., Huijie, Ch., Xiaowen, L. and Hui, W. (2025) "VR-empowered interior design: Enhancing efficiency and quality through immersive experiences", [online], School of Plastic Arts, Daegu University, School of Fine Arts and Design, Yulin Normal University, School of Art and Design, Yancheng Institute Of Technology, https://www.sciencedirect.com/science/article/pii/S0141938224002518

Hamacher, A. (2021) "Stereoscopy in Virtual Reality", [online], Kwangwoon University, https://ijettjournal.org/Volume-69/Issue-6/IJETT-V69I6P219.pdf

Suwandi, G., Khotimah, S., Haryanto, F. and Suprijadi, S.. (2024) "Effect of Virtual Reality Video Frame Rate on Visually Induced Motion Sickness Through Electroencephalography Measurement", [online], https://www.researchgate.net/

publication/383500602_Effect_of_Virtual_Reality_Video_Frame_Rate_on_Visually_Induced_Motion_Sickness_Through_Electroencephalography_Measurement

Fedotova, N., Procenko, M., Baranowa, I., Dehtiarenko, Y. and Waszczenko, S. (2023) "RESEARCH ON CALCULATION OPTIMIZATION METHODS USED IN COMPUTER GAMES DEVELOPMENT", [online], Sumy State University, Faculty of Electronics and Information Technologies, Department of Information Technology, Sumy, Ukraine, Lublin University of Technology,Faculty of Electrical Engineering and Computer Science, Lublin, Poland, https://www.researchgate.net/publication/374347021_RESEARCH_ON_CALCULATION_OPTIMIZATION_METHODS_USED_IN_COMPUTER_GAMES_DEVELOPMENT

Boonsawang, N. and Motonobu, K. and Chanpum, P.(2024) "Optimizing Art and Technology in 3D Character Creation: Strategies for High-Fidelity Modeling and Resource Efficiency in Real-Time Environments", [online], Rangsit University, https://www.researchgate.net/publication/382083358_Optimizing_Art_and_Technology_in_3D_Character_Creation_Strategies_for_High-Fidelity_Modeling_and_Resource_Efficiency_in_Real-Time_Environments

Qiongxian, Zh. (2024) "Advanced techniques and high-performance computing optimization for real-time rendering", [online], Monash University, Clayton, Australia, https://www.researchgate.net/publication/383475110_Advanced_techniques_and_high-performance_computing_optimization_for_real-time_rendering

Fonseca, A. (2018) "3D Modeling Pipeline for Games Work Methods for Low Poly Models with Hand Painted Textures", [online], Tampere University of applied sciences, https://www.theseus.fi/bitstream/handle/10024/156811/Gomes_Sarmento_Da_Fonseca_Ana.pdf?sequence=1&isAllowed=y

Webster, N. (2017) "High poly to low poly workflows for real-time rendering", [online], https://www.researchgate.net/publication/316435393_High_poly_to_low_poly_workflows_for_real-time_rendering

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