UDC 621.314
IRSTI 67.09.33
RESEARCH ARTICLE

EVOLUTION OF FORMATION IN POST-DIGITAL ARCHITECTURE

B. Assimov

Selcuk University , 42130, Konya, Turkiye

Abstract. *This comprehensive study critically interrogates the ontological paradigm shift towards post-digital architecture, defining it not merely as a stylistic evolution but as a fundamental transition where digital technologies recede from being visible effects to becoming an invisible, ambient medium that orchestrates material, sensory, and algorithmic processes. The relevance of this research lies in understanding architecture as a dynamic system governed by project-specific computational logics and complex data-driven rules, challenging conventional focus on static object-making and universal stylistic codes. The investigation employs a rigorous, multi-layered hybrid methodology across five experimental cases: (1) AI-driven generative design for real-time morphogenetic visualization; (2) automated material retexturing using generative algorithms to create adaptive skins; (3) AI-assisted heritage reconstruction to explore speculative historical adaptations; (4) hybrid digital-physical prototyping via 3D printing to validate structural integrity; and (5) immersive 1:1 scale evaluation in Virtual Reality using Unreal Engine and Oculus Quest 2. This integrated approach allows assessment of post-digital forms from computational, perceptual, and material perspectives. Key results demonstrate that architectural forms emerge as adaptive, multi-agent systems: AI introduces coherent yet unpredictable variations expanding the design search space; VR simulations reveal spatial and ergonomic discrepancies often invisible in traditional CAD; and physical prototyping establishes a critical feedback loop between digital plasticity and material constraints. The study concludes that the architect's role has shifted from a solitary author of fixed forms to a curator of evolutionary processes and human-machine symbiosis, highlighting the potential of hybrid methodologies to reconcile computation, materiality, and perception in contemporary architectural practice.*

Keywords: *post-digital architecture, form-making, AI, VR modeling, 3D printing, generative algorithms, phygital design*

***Corresponding author**
Bakhadyr Assimov, e-mail: bahadyr.asimov@gmail.com

https://doi.org/10.51488/1680-080X/2025.4-02
Received 04 November 2025; Revised 18 December 2025; Accepted 28 December 2025

ӘОЖ 621.314
ҒТАМР 67.09.33
ҒЫЛЫМИ МАҚАЛА

ПОСТ-ЦИФРЛЫҚ СӘУЛЕТТЕГІ ПІШІН ҚАЛЫПТАСТЫРУ ЭВОЛЮЦИЯСЫ

Б. Асимов

Селчук университеті, 42130, Конья, Түркия

Аңдатпа. *Бұл кешенді зерттеу пост-цифрлық сәулетке бағытталған онтологиялық парадигмалық ауысымды сыни тұрғыдан қарастырады, оны тек стильдік эволюция ретінде емес, цифрлық технологиялардың көрінетін эффектілерден шегініп, материалдық, сезімдік және алгоритмдік процестерді үйлестіретін көрінбейтін, ортақ ортаға айналатын түбегейлі трансформация ретінде анықтайды. Зерттеудің өзектілігі сәулетті жобалық-спецификалық есептеу логикалары мен деректерге негізделген күрделі ережелер арқылы басқарылатын динамикалық жүйе ретінде қарастыруға, сондай-ақ дәстүрлі статикалық объект жасауға және әмбебап стильдік кодтарға бағытталған тәсілдерді қайта қарауға мүмкіндік береді. Зерттеу бес эксперименттік жағдайды қамтитын көпқабатты гибридтік әдістемені қолданады: (1) нақты уақыттағы морфогенетикалық визуализация үшін ЖИ-негізделген генеративті дизайн; (2) бейімделетін қабықтарды қалыптастыру үшін генеративті алгоритмдер арқылы материалды автоматты түрде қайта текстуралау; (3) спекулятивті тарихи бейімдеулерді зерттеу мақсатында ЖИ көмегімен мұра нысандарын реконструкциялау; (4) құрылымдық тұтастықты тексеру үшін 3D-басып шығару арқылы гибридтік цифрлық-физикалық прототиптеу; (5) Unreal Engine және Oculus Quest 2 арқылы 1:1 масштабтағы VR иммерсивті бағалау. Нәтижелер пост-цифрлық формалардың бейімделгіш, көпагентті жүйелер ретінде қалыптасатынын көрсетеді: ЖИ дизайн іздеу кеңістігін кеңейтіп, бірізді, бірақ болжап болмайтын вариацияларды енгізеді; VR симуляциялары дәстүрлі CAD-та көрінбейтін кеңістіктік және эргономикалық сәйкессіздіктерді анықтайды; ал физикалық прототиптеу цифрлық пластикалылық пен материалдық шектеулер арасындағы қажетті кері байланыс циклін қалыптастырады. Зерттеу сәулетшінің рөлі түбегейлі өзгергенін көрсетеді: ол енді бекітілген формалардың жеке авторы емес, эволюциялық процестер мен адам-машина симбиозының кураторы болып табылады.*

Түйін сөздер: *пост-цифрлық сәулет, пішін қалыптастыру, ЖИ, VR модельдеу, 3D басып шығару, генеративті алгоритмдер.*

***Автор-корреспондент**
Бахадыр Асимов, e-mail: bahadyr.asimov@gmail.com

https://doi.org/10.51488/1680-080X/2025.4-02
Алынды 04 қараша 2025; Қайта қаралды 18 желтоқсан 2025; Қабылданды 28 желтоқсан 2025

УДК 621.314
МРНТИ 67.09.33
НАУЧНАЯ СТАТЬЯ

ЭВОЛЮЦИЯ ФОРМООБРАЗОВАНИЯ В ПОСТ-ЦИФРОВОЙ АРХИТЕКТУРЕ

Б. Асимов

Университет Сельчук, 42130, Конья, Турция

Аннотация. *Данное комплексное исследование критически анализирует онтологический парадигмальный сдвиг в сторону постцифровой архитектуры, рассматривая её не просто как стилистическую эволюцию, а как фундаментальную трансформацию, в рамках которой цифровые технологии перестают быть видимыми эффектами и становятся невидимой, средовой инфраструктурой, координирующей материальные, сенсорные и алгоритмические процессы. Актуальность исследования заключается в рассмотрении архитектуры как динамичной системы, управляемой проектно-специфическими вычислительными логиками и сложными правилами, основанными на данных, что позволяет оспорить традиционное внимание к статичному формообразованию и универсальным стилевым кодам. Для анализа применена строгая многоуровневая гибридная методология на пяти экспериментальных кейсах: (1) генеративное проектирование на основе ИИ для морфогенетической визуализации в реальном времени; (2) автоматизированная ретекстуризация материалов с использованием генеративных алгоритмов для создания адаптивных оболочек; (3) реконструкция объектов архитектурного наследия с ИИ для изучения спекулятивных исторических адаптаций; (4) гибридное цифрово-физическое прототипирование с использованием 3D-печати для проверки конструктивной целостности; (5) иммерсивная оценка в масштабе 1:1 в VR с Unreal Engine и Oculus Quest 2. Результаты показывают, что постцифровые формы проявляются как адаптивные многоагентные системы: ИИ вносит согласованные, но непредсказуемые вариации, расширяя пространство проектного поиска; VR-симуляции выявляют пространственные и эргономические несоответствия, часто незаметные в традиционном CAD; физическое прототипирование обеспечивает критический контур обратной связи между цифровой пластичностью и материальными ограничениями. Исследование делает вывод, что роль архитектора радикально изменилась: теперь он не является единоличным автором фиксированных форм, а выступает куратором эволюционных процессов и симбиоза человека и машины.*

Ключевые слова: *пост-цифровая архитектура, формообразование, ИИ, VR моделирование, 3D печать, генеративные алгоритмы.*

***Автор-корреспондент**
Бахадыр Асимов, e-mail: bahadyr.asimov@gmail.com

https://doi.org/10.51488/1680-080X/2025.4-02
Поступила 04 ноября 2025; Пересмотрено 18 декабря 2025; Принято 28 декабря 2025

ACKNOWLEDGEMENTS/SOURCE OF FUNDING

The research was conducted using private sources of funding.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

We are witnessing a fundamental shift in the history of architecture. In the 21st century, the discipline has entered the post-digital era, where digital technologies cease to be merely external tools or superficial effects. Digitalization moves beyond being a showcase for form to become an invisible medium, akin to electricity or the internet. Consequently, architecture transforms from a static object into a dynamic system shaped by data flows, sensory networks, and algorithmic models. In this new reality, the ontology of the architectural work itself undergoes a transformation. The traditional notion of a building as a static object in stone or concrete evolves into the concept of architecture as an ongoing process. Design no longer concludes with construction; it continues through algorithmic adaptation scenarios and real-time user interaction **(Assimov, 2025)**. This requires architects to shift from total control over the outcome to creating open, self-developing systems capable of responding to environmental variables.

In this context, the traditional categorization of style becomes less relevant. Post-digital architecture moves away from a single aesthetic code and fixed form. Instead, each project develops a unique character, forming its own internal logic-an individual algorithmic rule set that governs composition, functional logic, and material realization. These project-specific systems allow architects to integrate historical knowledge, biological principles, and computational models into adaptive, unique frameworks **(Kolarević, 2003; Spiller, 2018)**. The relevance of this research lies in the increasing need for architectural practices that are responsive to environmental conditions, user behavior, and rapidly evolving technological contexts. Unlike conventional methods, which often rely on fixed forms and predetermined styles, post-digital processes enable the exploration of complex geometries, adaptive systems, and context-aware design decisions.

The scientific problem addressed in this study concerns the reconciliation of computational capabilities with architectural intent. While algorithmic models and data-driven tools can produce a wide range of design outcomes, they do not inherently account for cultural, spatial, or functional considerations. Architects must, therefore, act as curators, guiding generative processes to achieve contextually appropriate, human-centered, and aesthetically coherent solutions. This challenge becomes particularly evident when evaluating large-scale projects, complex geometries, or experimental forms that require iterative assessment in both virtual and physical environments.

The aim of this study is to investigate how hybrid workflows-combining computational design, virtual reality, and physical prototyping-can enhance the design process in post-digital architecture. The objectives include: (1) analyzing the impact of immersive virtual environments on spatial perception, material understanding, and ergonomic evaluation; (2) examining the role of algorithmic and generative modeling in creating adaptive, context-sensitive designs; and (3) assessing how iterative digital-physical workflows improve design accuracy and decision-making efficiency.

Recent literature highlights the transformative potential of post-digital approaches. Architecture is no longer a fixed endpoint but an ongoing, adaptive process where algorithmic scenarios and real-time interactions extend the life of design beyond construction **(Assimov, 2025)**. Computational models and parametric methods are important for producing flexible design frameworks that integrate environmental responsiveness, material behavior, and functional logic **(Kolarević, 2003)**. Project-specific algorithmic rule sets enable architects to manage complexity while preserving spatial coherence and design intent **(Spiller, 2018)**. Collectively, these studies indicate that contemporary architectural practice benefits from embracing hybrid methodologies, where digital tools are embedded within the workflow rather than serving as decorative or illustrative adjuncts.

In summary, the post-digital era challenges architects to redefine the boundaries of design authorship, aesthetic judgment, and technical expertise. By framing architecture as a dynamic, adaptive process, this study positions hybrid digital-physical workflows as essential for addressing contemporary design challenges. Understanding and implementing these methods not only improves the precision, efficiency, and experiential quality of architectural outcomes but also informs the evolving role of architects as curators of computationally mediated, contextually grounded architectural systems.

2 LITERATURE REVIEW

Post-digital architecture serves as both a continuation and a transformation of digital architecture, which emerged in the late 1990s with the development of parametric and algorithmic design **(Oxman, 2006; Carpo, 2017)**. In the initial digital era, architects utilized software tools such as Rhino, Grasshopper, and Maya to create complex geometries, where form often remained the primary indicator of architectural skill **(Schumacher, 2011)**. In contrast, post-digital architecture treats the digital environment as an integrated ecosystem in which algorithmic, sensory, and material processes collectively shape the architectural form **(Gu, 2021; Nabiyev et al., 2024)**. This approach recognizes that architecture is no longer a static outcome but a dynamic process, integrating computational, virtual, and physical dimensions to inform decision-making at all stages of design.

This paradigm shift aligns with the phygital concept-the integration of physical and digital spaces-where design ceases to be merely a visual or material practice and becomes a system of data, algorithms, and environmental interaction **(Caetano et al., 2020)**. In post-digital workflows, architects can simulate environmental conditions, material responses, and spatial interactions within VR or AI-assisted platforms before any physical construction begins. Consequently, the architect's role evolves from a creator of fixed forms to a curator of evolving conditions, managing algorithmic rules, virtual experiences, and physical feedback loops simultaneously. Design is treated as an iterative process in which digital modeling, immersive visualization, and physical prototyping inform each other, producing adaptive and contextually sensitive architectural solutions **(Kolarević, 2003; Spiller, 2018)**.

Contemporary studies confirm that managing a set of rules and constraints from which a unique object emerges defines a new professional identity **(Schumacher, 2011; Oxman, 2006)**. Post-digital design emphasizes project-specific logic, where each architectural work develops its own internal algorithmic language, integrating historical knowledge, biological principles, and computational models. This allows architects to address complex environmental and cultural contexts while preserving spatial coherence and design intent. For example, hybrid workflows combining VR, 3D printing, and AI-assisted generative tools enable iterative testing of form, materiality, and ergonomics, improving decision-making speed and reducing errors in both professional and educational settings.

Furthermore, recent scholarship emphasizes the pedagogical implications of this shift, suggesting that experimental architectural studios function as laboratories for testing human-machine collaborations **(Andersen et al., 2023)**. Students and professionals alike benefit from immersive and interactive workflows, where full-scale VR exploration allows immediate perception of spatial scale, material behavior, and lighting conditions. Physical prototyping via 3D printing complements virtual testing by exposing geometric inconsistencies and structural constraints, creating a continuous feedback loop between digital design and tangible outcomes. This integration of digital and physical workflows supports an experiential learning environment that is difficult to achieve through traditional 2D drawings or static renders alone.

Existing research tends to focus on individual aspects of post-digital architecture: generative design, VR applications, AI integration, or phygital spaces. However, gaps remain in the current literature. First, there is insufficient integration of all elements-algorithmic logic, VR/AR, AI, new materials, and physical environment-within a single study. Second, there is a lack of experimental research demonstrating the impact of these technologies on the form-making process. Third, current methodologies rarely provide systematic evaluation of the architect's role as a curator of dynamic processes across digital and physical domains. These limitations hinder the broader understanding of how post-digital methodologies can be operationalized in both educational and professional contexts.

These gaps highlight the need for comprehensive experimental research combining algorithmic design, VR/AR, AI, and physical realization. This study addresses these needs by providing both empirical and theoretical foundations for a new paradigm of form-making. By structuring the design workflow around iterative feedback between digital, immersive, and physical environments, architects and students gain the ability to explore complex forms, test spatial and material decisions, and validate conceptual choices before construction. Ultimately, post-digital architecture positions the architect as a curator of evolving systems, blending human creativity with computational adaptability to produce responsive, context-aware, and innovative architectural solutions.

3 MATERIALS AND METHODS

The Five independent experimental cases were conducted to explore the role of artificial intelligence, immersive virtual environments, game-based simulations, and hybrid digital-physical processes. Each experiment represents an autonomous methodological module, demonstrating various trajectories of human-algorithm-environment interaction.

Methodological Framework and Research Type

This study is positioned within the methodological framework of Research through Design (RtD), complemented by a multiple-case study approach. While the research incorporates experimental procedures and measurable outputs, its primary aim is not hypothesis testing under controlled laboratory conditions, but the generation of architectural knowledge through iterative design actions, reflective practice, and project-based experimentation.

In this context, each experiment functions as an autonomous design-research case, where architectural form is produced, evaluated, and reconfigured through the interaction of the architect, computational systems, and material constraints. The role of the researcher is simultaneously that of designer and observer, aligning the study partially with action research, where design decisions actively influence the research process itself.

The methodological structure emphasizes process-oriented inquiry rather than object-oriented validation. Architectural knowledge is derived from comparative analysis across five experimental cases, focusing on how AI, VR, game engines, and digital-physical hybridization affect form-making, spatial perception, and material realization.

The limitations of this approach are acknowledged. The experiments are conducted by a single experienced architect, and the evaluation criteria are primarily qualitative, supported by selective quantitative measurements (e.g., scale, volume, surface area, production time, and dimensional accuracy). Therefore, the findings are not intended to be statistically generalizable but are analytically transferable, offering methodological insights applicable to architectural design research, education, and professional practice.

By explicitly framing the study as design-research, this paper contributes to the growing body of post-digital architectural scholarship where form emerges as an evolutionary process and architectural knowledge is produced through making, testing, and reflection.

The research methodology integrates four key post-digital design tools:

1.AI Retexturing - Algorithmic transformation of textures, lighting, and micro-details of objects.

2.1:1 VR Modeling - Immersive study of space and form.

3.3D Printing - Transfer of digital morphology into the physical environment for stability and proportion analysis.

4.Game Engine Simulations - Investigation of object behavior in dynamic scenarios considering user and environmental interaction.

These methods are combined in a cyclical process forming the form genome, where architectural form is considered an evolutionary process, and the architect functions as a curator of a multi-agent system.

Experimental Cases

This section presents a series of experimental cases that investigate the intersection of artificial intelligence, virtual environments, and physical fabrication in contemporary architectural design. These experiments explore how generative algorithms, immersive visualization, and hybrid workflows can influence the evolution of form, materiality, and spatial perception. By examining these cases, the study aims to highlight the shifting role of the architect - from a traditional author of static representations to a curator and facilitator who guides the dynamic interplay between digital processes, human input, and physical realization.

The experiments collectively illustrate a transition from conventional, object-oriented design approaches to process-driven, adaptive methodologies. Architectural forms are treated as evolving entities, continuously shaped by computational algorithms, environmental data, user interactions, and material constraints. Through this lens, AI is not seen as a replacement for human creativity but as an enabling tool that expands the designer's capacity to generate, evaluate, and refine complex solutions at multiple scales.

Furthermore, these cases demonstrate the potential of hybrid workflows that merge digital and physical environments. From initial sketches and 3D modeling in virtual reality to AI-enhanced visualization and tangible prototyping through 3D printing, the experiments show how architects can test and iterate designs while balancing conceptual intent with structural and material feasibility. Collectively, these projects reveal how immersive, AI-driven design methodologies can foster innovation, allowing architects to engage with both speculative and practical dimensions of architecture simultaneously.

Ultimately, this collection of experimental cases provides a comprehensive framework for understanding how emerging technologies can inform innovative, contextually responsive, and resilient architectural practices, offering a glimpse into the future of post-digital design. These investigations also emphasize the importance of continuous experimentation and reflection, reinforcing the notion that architectural knowledge evolves through iterative exploration and adaptive practice.

Declaration on the Use of Artificial Intelligence This study utilized AI-based tools (MidJourney, Krea AI, LookXAi) exclusively for conceptual visualization and experimental form exploration. All prompts were authored by the researcher. The generated images are treated as synthetic data outputs rather than artistic works claiming copyright. The author declares full responsibility for the selection, curation, and ethical use of these AI-generated visualizations within the context of this research.

Experiment 1 - Form-Making in a Virtual Environment Using AI and Real-Time Visualization

This experiment was conducted by a single individual within the framework of existing technical infrastructure and accessible facilities. The person conducting the experiment is an experienced architect and the author of this article. The applicability of the experiment spans a wide range; it can be utilized in professional environments, design centers, architecture and design offices, schools, and educational institutions, as well as individually to support the design process.

The primary objective of the experiment is to create a desired model in a completely virtual environment, at a 1:1 scale, using a freeform design approach. Designs can be modeled as rough masses or in detail, and these draft designs can be visualized in real-time with artificial intelligence support. Thus, the user can simultaneously observe the near-realistic visualized state of the design with which they are interacting one-on-one. This study plays a significant role - especially during the concept phase - ranging from industrial design to architectural design, and from urban planning to fashion design. **(Figure 1)**.

Figure 1 - 3D modeling in virtual environments

Figure 1 illustrates examples of 3D modeling in virtual environments. The workflow includes automotive design modeling (a, b) and fashion design modeling (c, d) conducted within Gravity Sketch. All images were sourced from the official Gravity Sketch website.

At the beginning of the experiment, the Oculus Quest 2 device was launched, and a remote connection was established via the Meta Horizon application for data exchange with computers. By accessing the Meta Horizon application from the computer as well, screen sharing was initiated from the Oculus Quest 2 device, allowing operations performed on the device to be projected onto the computer screen. In this way, drawings made with the VR headset were instantaneously transferred to the computer display. Subsequently, the Gravity Sketch application was opened on the Oculus Quest 2 headset and prepared for drawing. Gravity Sketch offers the user 3D modeling with 0.1 mm precision, 1:1 scale manipulation, layer management, and real-time simulation capabilities. The user can customize their design in the 3D environment by selecting different brush types, pen sizes (ranging from 0.5-5 cm), and density settings.

On the computer, the Krea AI platform was accessed, “Screen Mode” was activated, and the visual instruction to be used within the scope of the experiment was entered into the prompt input field:

A large residential high-rise complex surrounded by a dense green forest, four modern skyscrapers placed symmetrically on a rectangular plot, clean white masterplan background, realistic lighting, top-view aerial render, smooth curved internal roads, minimalistic urban context, high-detail trees, soft shadows, professional architectural visualization, 8K ultra-realistic, isometric camera.

Additionally, the influence of artificial intelligence on the visualization was adjusted - specifically, determining how faithful the output would remain to the projected image and the extent of AI intervention. AI parameters included values such as generative fidelity (0-100%), color accuracy (0-100%), material reflection intensity (0-1.0), and shadow softness (0-1.0); in this experiment, fidelity was set to 85% and shadow softness to 0.7. The experiment process began with the instantaneous projection of drawings made in the Gravity Sketch application onto the Krea AI platform. The artificial intelligence produced realistic and high-resolution (8K, 7680x4320 pixels) visualizations in line with the transmitted visual data and the entered prompt. Each change was processed by the system within an average of 1.2 seconds, providing real-time feedback to the user.

Within the scope of the experiment, five different masses proportional to a bird's-eye perspective were created to evaluate conceptual ideas, and various variations of structures, road networks, and green areas were rapidly analyzed through them. Volume, surface area, and perimeter ratios were measured for each of these masses; the total model volume was determined as 12,450 m^3, and the total surface area as 8,230 m^2. Road and green area ratios were 32% and 18% of the total parcel area, respectively. The average building height of the model was calculated as 45 m, with a maximum height of 60 m. These numerical data demonstrate that the experiment can produce measurable outputs in terms of architectural planning.

The advantages provided by this workflow are multifaceted. In traditional methods, architects model ideas during the concept phase using 2D sketches or desktop-based tools. This process can be time-consuming. In this study, however, the user could draw freely without standard peripherals, determining the line's route with gestures in a 1:1 scale environment. Gravity Sketch's advanced settings, such as 3D snap grid (0.5 cm precision), layer opacity (0-100%), curve smoothing (0-10), and dynamic scaling (0.1-10x), optimize the design process. These parameters directly affect the accuracy, detail density, and visualization speed of the design.

In educational environments, instead of drawing 2D on a board or preparing physical models during lectures, teachers can present visual and interactive content within minutes using VR headsets and Krea AI support. In offices, concept works can be completed in a short time at the start of a project. The Gravity Sketch application not only offers basic drawing tools but also provides detailed modeling capabilities with a diverse and rich library of drawing tools. The user can optimize their design using different brush types, pen options, measurement tools, and 3D mass manipulation functions **(Figure 2)**.

The hardware and software tools used in the experiment are as follows:

MSI Laptop Pulse GL76 11UEK: Intel Core i7-11800H, 8 cores / 16 threads, boost frequency up to 4.6 GHz, 32 GB DDR4 RAM, NVIDIA RTX 3060 Laptop GPU 6 GB VRAM, NVMe SSD 1.84 TB.

Oculus Quest 2 VR Headset: 1832x1920 pixel resolution, 120 Hz refresh rate, 6DoF (six degrees of freedom) tracking system, suitable for long-duration experiments with a 72-hour battery life.

Meta Horizon Application: Low latency (average 20 ms) data transfer and screen sharing between the VR device and the computer.

Gravity Sketch: 3D freeform modeling, layer management, dynamic scaling, snap grid, curve smoothing, VR-based real-time manipulation.

Krea AI: 8K ultra-realistic visualization, prompt-based generative AI, real-time render time averaging 1.2 s, fidelity, and shadow intensity control.

During the experiment, the system's performance was measured in detail; data transfer latency for each change occurred in the 0.8-1.5 second range, and the render time averaged 1.2 seconds. In terms of user experience, every line drawn by hand and every model change was processed by the system at over 60 fps, offering a fluid VR experience.

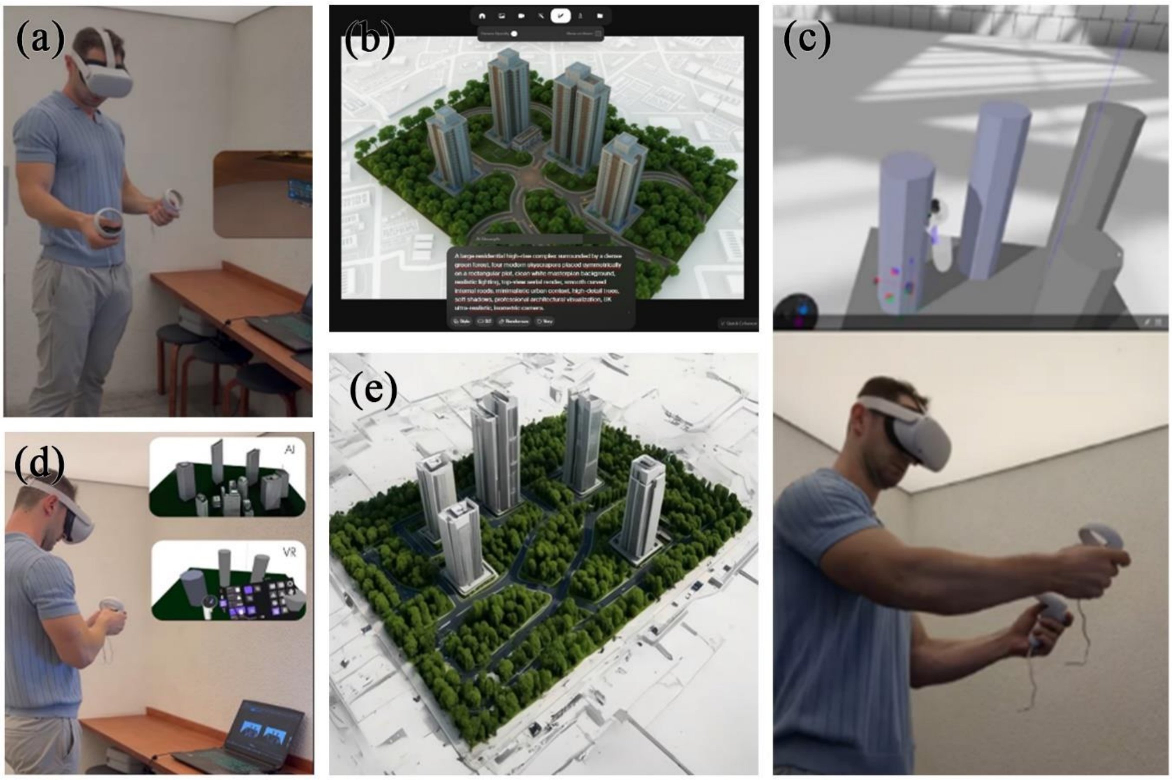

Figure 2 - Form-Making in a Virtual Environment Using AI and Real-Time Visualization [author's material].

Figure 2 illustrates the VR-assisted 3D modeling workflow conducted entirely by the author. The Oculus Quest 2 was set up for 3D modeling (a), after which the Krea AI tool was launched, a prompt was entered, and the modeling process was initiated (b). Masses were created in Gravity Sketch (c), while the visualized representation of the model was simultaneously monitored using the Krea AI tool (d). Finally, the visual output generated with Krea AI based on the masses modeled in Gravity Sketch is presented (e).

Experiment 2 - Generative Retexturing and Automated Visual Representation

While this experiment was conducted individually, the workflow is applicable for architects, industrial designers, and urban planners. The primary objective is to perform material assignment and visualization of 3D models rapidly and effectively with AI support, while preserving structural integrity. Rather than generating visuals from scratch, the focus is on optimizing material, lighting, and texture parameters on an existing model to generate diverse alternatives.

Two main modeling tools were used in the experiment process: Autodesk Maya and Rhinoceros 8. The initial concept form stage was carried out on Autodesk Maya due to its freeform modeling capabilities and animation-supported tools. In Maya, models were created using vertex manipulation with 0.01 unit precision, NURBS and polygon-based modeling, detailing with SubD (subdivision surface), and scale parameters (ranging from 0.001-10 units). After modeling was completed, the models were transferred to Rhinoceros for detailing and scaling operations, where they were revised using advanced technical features such as Layer Management, Surface Analysis, Curvature Analysis, History Recording, and precise measurement (0.1 mm precision).

The projects modeled in the study are: Ski Snow Cabin, Luxury Villa (Exterior and Interior), and Speculative Research Center. Models finalized in Rhinoceros were processed with MidJourney's Retexture feature. This feature can reassign material, texture, and light parameters of the existing image based on the entered prompt and can also optimize technical settings such as texture depth (0-10), reflection intensity (0-1.0), shadow softness (0-1.0), and global illumination (0-100%).

In Rhinoceros, regions on the model's facade to be assigned different materials were marked with RGB color codes, which increased the AI's accuracy rate in the material assignment process.

After deciding on the model's render angle, screenshots were exported in jpg or png format at 3840x2160 pixel (4K) resolution. These visuals were uploaded to the MidJourney Retexture platform and the prompt was entered:

Bird eye view of a luxury villas made by white concrete features curve and fluid architecture, lush vegetation and forest located in seaside, luxury black car, people walking, grass, road, ultra realistic.

The AI influence level was determined as a minimum of 10/100 and can be increased if necessary. Additionally, a sample image from previous works or the internet was uploaded for the design's style reference, followed by the selection of image count and alternative ratio. After completing all settings, the "Submit Retexture" button was pressed, and numerous alternative renders were presented to the user.

The most suitable visual selected from the alternatives was revised using MidJourney's Edit function. For example, removal of background trees, modification of building details, or light-shadow adjustments were performed via prompts; in the post-production process, parameters such as HDR mapping (0-100), brightness/contrast (0-100), and gamma correction (0-5.0) were optimized.

The obtained visuals can be converted into animation using the Kling AI platform if necessary. For animation production, the visual was uploaded in 4K resolution and the prompt was entered as follows:

Ultra-luxury modern villa with large glass facades and warm ambient lighting, elegant landscape design, palm trees and soft garden lights. People walking naturally in front of the building, realistic human motion, a premium sports car driving slowly on the driveway. Dynamic cinematic shot, camera slowly approaching the villa from a wide angle to a close-up, smooth dolly-in movement, shallow depth of field, soft evening sunlight, high-end architectural animation style, 4K ultra-realistic, physically accurate reflections, natural shadows, high-detail textures, premium CGI film quality.

Animation duration was set to 5-10 seconds, frame rate 60 fps, motion blur 0.7, depth of field 0.5, and global illumination 80%. Thanks to this method, render and animation processes that previously took hours or days can be obtained with numerous alternatives within minutes using AI support. For instance, in the Luxury Villa model, a total of 12 render alternatives were produced in 4 minutes, and the animation time was measured as 6-8 minutes.

Prior to the experiment, visualization of designs created with 3D modeling tools was a long process requiring high technical knowledge. Designers had to manually perform material assignment, light, and texture settings, and re-run the render engine for every revision; this process could take hours or even days. Post-experiment, thanks to the AI-supported process, numerous alternatives could be rapidly produced on the same model, material and light optimization was provided automatically, and animations could be created in a short time. This significantly accelerated rapid iteration, visual decision-making, and design revisions during the concept design process. Furthermore, since modeling and visualization times were shortened in educational and office environments, teachers and designers could prepare and present visual content within minutes, while project teams gained the opportunity for rapid prototyping and iteration **(Figure 3)**.

To enable a clear before-and-after comparison, the visualization workflow was quantitatively evaluated in terms of production time and output variability. Prior to AI integration, the preparation of a single high-quality render with manual material and lighting setup required approximately 2-4 hours, while short animation production typically exceeded 6-8 hours. After the implementation of the AI-supported workflow, equivalent render outputs were generated within 3-5 minutes, and animations of 5-10 seconds were completed within 6-8 minutes. In addition, the number of visual alternatives increased from 1-2 manually produced outputs to 10-15 AI-generated variations per model.

Hardware and software tools used in the experiment:

MSI Laptop Pulse GL76 11UEK: Intel Core i7-11800H, 8 cores / 16 threads, boost frequency up to 4.6 GHz, 32 GB DDR4 RAM, NVIDIA RTX 3060 Laptop GPU 6 GB VRAM, NVMe SSD 1.84 TB.

Autodesk Maya: Polygon and NURBS-based modeling, SubD supported freeform design, vertex manipulation (0.01 unit precision), animation tools.

Rhinoceros 8: Layer Management, Surface Analysis, History Recording, precise measurements (0.1 mm precision), curvature analysis.

MidJourney (Retexture, Edit): AI-based material assignment, texture depth (0-10), reflection intensity (0-1.0), shadow softness (0-1.0), HDR mapping, prompt-based visualization.

Kling AI: 4K ultra-realistic animation, frame rate 60 fps, motion blur 0.7, depth of field 0.5, global illumination 80%, rapid render and animation production.

This experiment both accelerated the visualization and animation processes of modeled projects and increased their quality. Processes that took hours before the experiment were completed within minutes after the experiment, providing numerous alternatives and revision possibilities. The decision-making speed and visual communication capacity in the design process significantly increased.

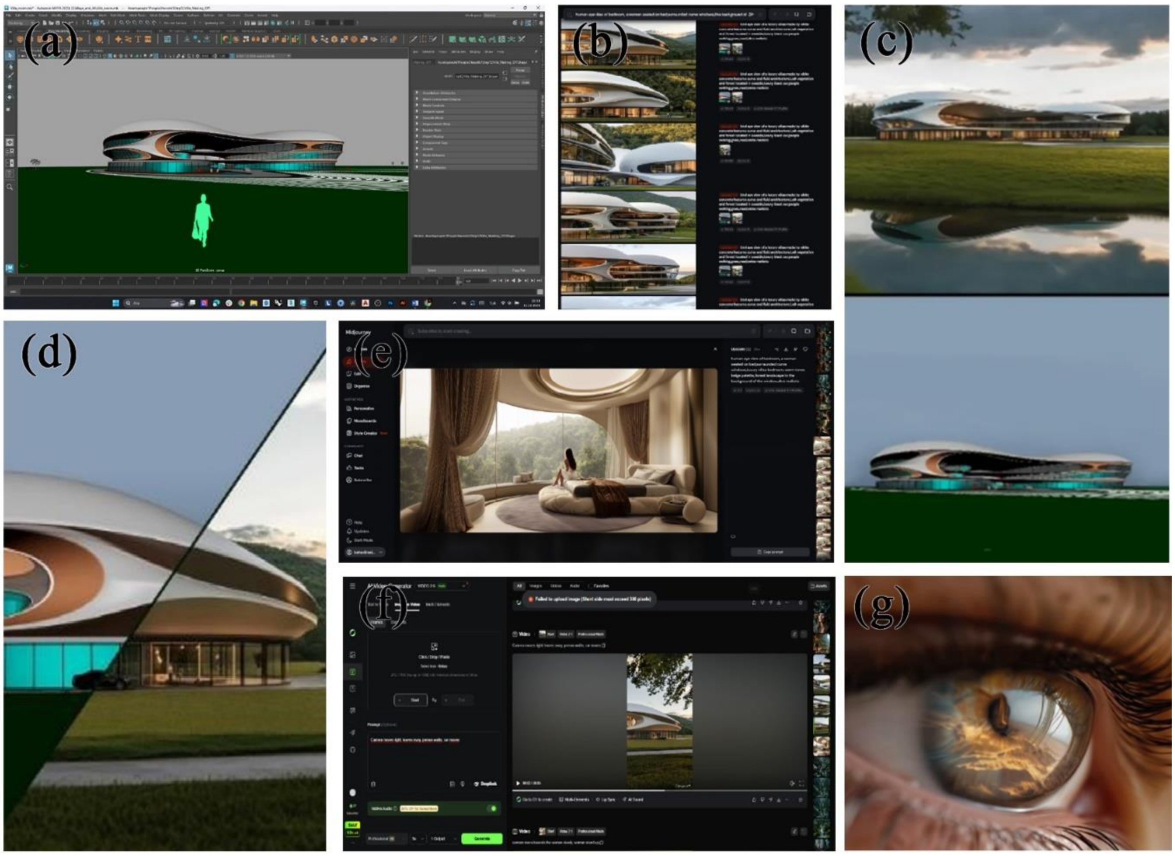

Figure 3 - Generative Retexturing and Automated Visual Representation [author's material].

Figure 3 illustrates the 3D modeling and visualization workflow conducted entirely by the author. A 3D model was developed using Autodesk Maya (a), followed by the application of materials through MidJourney's Retexture feature via prompt input (b). Comparisons between the 3D model screenshot and its visualization via MidJourney are presented (c, d). An interior image was produced entirely using MidJourney (e). The process of generating animations was conducted with the Krea AI tool (f), supplemented by additional visuals and animations created to support the animation (g).

Experiment 3 - Reconstruction of Architectural Heritage Using AI

This experiment was conducted entirely using artificial intelligence (AI), excluding traditional 3D modeling or post-production tools. The objective was to visualize an existing historical monument and imbue it with a future function through an innovative restoration process. The subject selected for the experiment is Whitby Abbey. Characterized by its Gothic architectural features, high arches, and distinctive silhouette, the structure presents complex geometric challenges for AI reconstruction.

The primary challenge was to generate a visual of the existing historical structure with high fidelity and to redesign it in accordance with the restoration process. This required accurately representing Gothic stone textures, fenestration, environmental context, and natural light-shadow relationships. The evaluation of visual accuracy and restoration quality was conducted through a comparative visual analysis method. The AI-generated outputs were compared with high-resolution archival photographs. Architectural elements such as arch proportions, window geometry, and material continuity were assessed qualitatively through expert-based visual inspection.

The experiment process was initiated using the MidJourney tool. In the first stage, the following expression was used as the prompt:

Whitby Abbey perspective, realistic rendering, detailed, blue sky, green grass, destroyed parts restored with glass.

With this prompt, high-resolution visuals were produced, with the generation of each image taking approximately 25-35 seconds. Over 100 alternative visuals were generated in total, and the one closest to the original was selected from among them. The selected visual was detailed using MidJourney's Edit feature; necessary regions were marked with the brush tool, and restoration and design additions were made using separate prompts for each region. This process was applied to increase visual accuracy and to reflect restoration details in the most correct manner.

In the restoration design, spaces were programmed for art exhibitions and creative workshops. The white, transparent structural elements added to the composition integrated with the natural environment, imparting a visual permeability to the building.

For animation production, the most suitable visual was selected and the LookXAi tool was utilized. The visual was animated in high resolution using AI-supported automatic animation algorithms. The user was able to determine the duration of the animation and obtain visualizations from different angles. This method allowed the visualization process, which could take days in traditional CAD and 3D animation software, to be completed in approximately 8-12 minutes. Furthermore, numerous alternatives were rapidly produced within the same timeframe, accelerating project design decisions.

Prior to the experiment, the visualization of historical structures and the modeling of restoration scenarios took hours, or even days, using CAD and 3D modeling processes. In these processes, both preserving original details and adding the restoration design required time and high technical expertise. Post-experiment, thanks to the AI-supported process, the same project could be visualized within minutes with high detail, from different angles, and with alternative design scenarios. This situation both increased the speed of design decision-making and enabled the rapid preparation of sample visuals in educational and project presentation settings.

The experiment also demonstrates the limitations of AI-based visual production systems. For instance, parametric and unique architectural structures like the Heydar Aliyev Center are designed through geometric continuities, control points, and structural necessities. Text-to-image generative models like MidJourney cannot exactly reproduce such structures requiring three-dimensional and dimensional accuracy. These models generate probabilistic predictions based solely on 2D visual patterns and pixel relationships; therefore, they do not understand the logic of the architectural form, and slight deviations occur during reproduction. The experiment reveals that, considering these limitations, AI can be used as a creative, visual, and conceptual tool, but must be supported by human expertise in structural productions requiring exact dimensional accuracy**(Figure 4)**.

Hardware and software tools used in the experiment:

MSI Laptop Pulse GL76 11UEK: Intel Core i7-11800H, 8 cores / 16 threads, boost frequency up to 4.6 GHz, 32 GB DDR4 RAM, NVIDIA RTX 3060 Laptop GPU 6 GB VRAM, NVMe SSD 1.84 TB.

MidJourney (Edit): Text-based visual generation and region-based editing, ultra-detailed visuals (~1.5M polygon equivalence).

LookXAi: AI-based animation production, high resolution, and automatic cinematic effects.

In conclusion, this experiment has shown that AI can provide a fast, detailed, and multi-alternative production capability in the restoration and redesign processes of historical structures, ranging from the concept phase to visualization and animation. Processes that previously took days were completed in minutes after the experiment, project design decisions were accelerated, and sampling capacity in educational/business environments was increased. Additionally, the experiment clearly demonstrated the limitations and potential areas of use for these tools by revealing the differences between architectural reproduction and visual representation.

Although no numerical similarity metric was applied, the consistency observed across multiple generated alternatives allowed the establishment of a repeatable qualitative assessment framework for AI-based architectural heritage visualization.

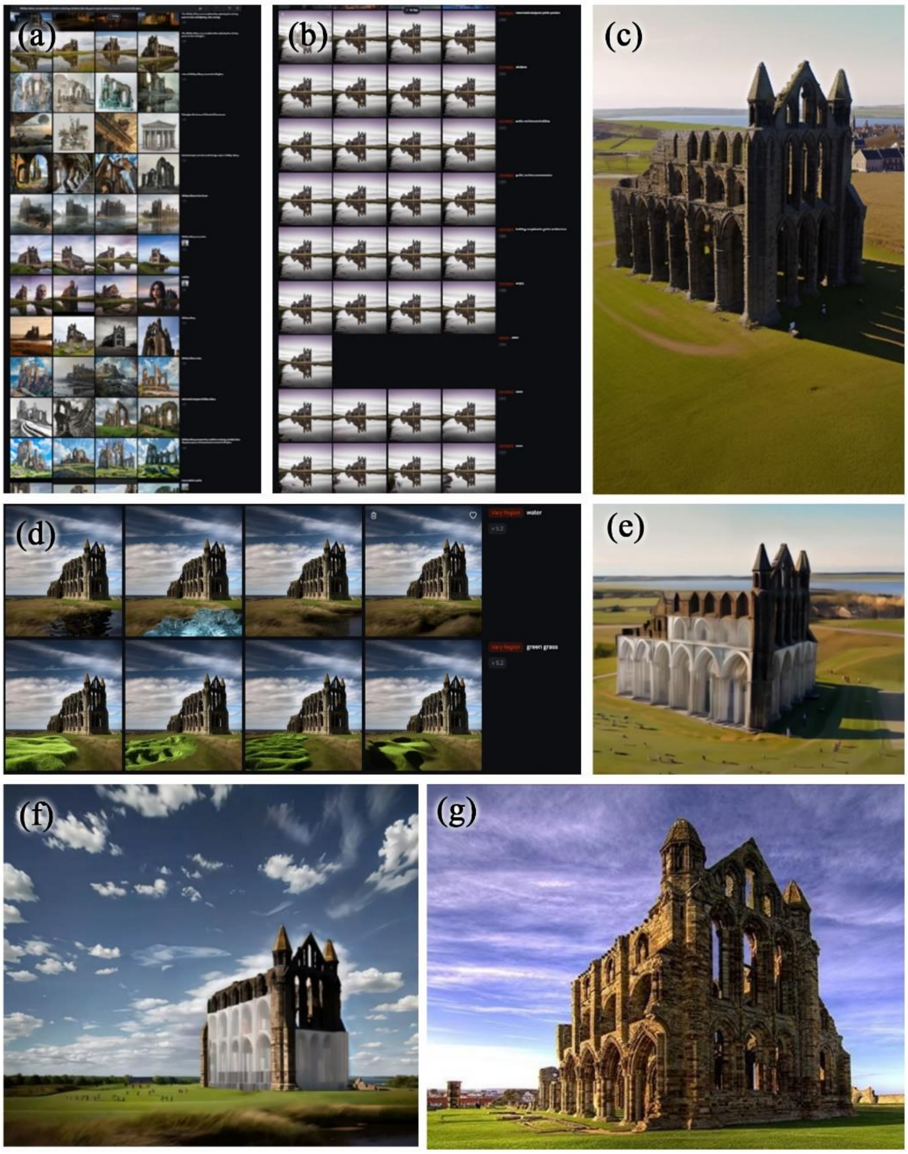

Figure 4 - Reconstruction of Architectural Heritage Using AI

Figure 4 demonstrates the process of recreating the original appearance of the structure using MidJourney. The workflow includes working in the MidJourney workspace to replicate the structure's original look (a, b), producing visuals closely resembling the original (c), and generating alternative versions with MidJourney's Edit feature (d). Restoration images were created using the Edit feature (e, f). For reference, the original picture of Whitby Abbey is provided (photograph by Chris Kirk) (g). All MidJourney-generated images were produced by the author.

Experiment 4 - Hybridization of Virtual Modeling and Physical Additive Fabrication

This experiment was conducted to investigate the transition processes from physical to digital and back to physical environments. The primary objective was to document the design workflow comprehensively and to evaluate the interaction, form accuracy, and production constraints between digital and physical realms. This experiment is applicable for both educational and professional contexts, providing insights into concept validation, design revision, and production optimization.

The experiment process began with outlining the main features on paper using traditional methods. This step allowed for the rapid conceptualization of the design idea and the execution of basic form analysis. Subsequently, the model was created in the virtual environment at a 1:1 scale with 0% error tolerance using the Oculus Quest 2 and Gravity Sketch. The model geometry was detailed with Gravity Sketch's Surface and Freeform tools, and the user could walk around the model in the virtual environment and experience the design at its actual scale. This stage is critical for observing the design's form, volume, and spatial relationships.

After modeling was completed, the model was converted to SUBD-based geometry using Rhinoceros 8 on the MSI Pulse G76 computer, and its suitability for 3D printing was technically ensured. In this phase, open surfaces that could cause problems during production were closed, the manifold structure was checked, and geometric integrity was established. Thus, the printability of the digital model was guaranteed. The model was then exported in STL format and prepared for transfer to the Bambu Lab X1 Carbon 3D printer.

The 3D printing process was carried out according to FDM-based desktop printer principles. The layer height was set to 0.15-0.2 mm, with X/Y axis accuracy of approximately ±0.05 mm and Z axis accuracy of ±0.02 mm. The filament used was PLA, with a printing temperature of 200-210°C, a print bed temperature of 60°C, and a print speed of 40-60 mm/s. For complex geometries, tree-type supports were used to facilitate post-print cleaning. Layer and infill settings were optimized with a 15% infill ratio, which is sufficient for prototypes. The resulting physical part showed a dimensional accuracy of approximately 95-98% compared to the digital model. This accuracy allowed the scale, form, and connection details of the design to be tested in the physical environment, experimentally verifying the relationship between digital input and physical output.

Structural integrity was evaluated at a prototype level through geometric stability, surface continuity, and deformation observation rather than mechanical load testing. During and after the printing process, the model was inspected for warping, layer separation, surface collapse, and support-induced deformation. No critical deformations were observed under the model’s self-weight, indicating sufficient stability for conceptual and form-validation purposes.

This study demonstrates the transformation of a design process, starting with traditional methods, into a 1:1 scale virtual model and then into a physical 3D prototype using modern technologies. Before the experiment, designers mostly worked with two-dimensional drawings or small-scale models, whereas after the experiment, designers can observe the design in 2D, 1:1 3D digital, and 3D physical formats, analyzing its pros and cons. This process increases designers' mastery over the project, provides opportunities for observation and experiencing the design, and helps them make faster and more conscious design decisions **(Figure 5)**.

The results of the experiment show the following:

The design process was accelerated by the transition from traditional to digital and from digital to physical; design ideas became more concrete and measurable.

Form and volume analyses could be performed in 1:1 scale and real-time with VR-based modeling, allowing the spatial relationships of the design to be directly experienced by walking around the model.

The 3D printing process provided the opportunity to physically test the geometric accuracy of the design, and production errors and structural issues were identified in advance **(Ujma et al., 2025)**.

In education, students can observe the conceptual design and physical prototype experience in the same process; in professional use, concept validation before prototyping and production can be done quickly and reliably.

Tools and technical specifications used:

MSI Laptop Pulse GL76 11UEK: Intel Core i7-11800H, 8 cores / 16 threads, boost frequency up to 4.6 GHz, 32 GB DDR4 RAM, NVIDIA RTX 3060 Laptop GPU 6 GB VRAM, NVMe SSD 1.84 TB.

Oculus Quest 2: VR headset, 1832×1920 pixels/eye, 72-90 Hz refresh rate, 6 DoF motion tracking.

Gravity Sketch: 1:1 scale freeform modeling, Surface and Freeform tools, real-time VR interactive design.

Rhinoceros 8: SUBD-based modeling, geometric correction suitable for 3D printing.

Bambu Lab X1 Carbon: FDM-based 3D printer; layer height 0.1-0.2 mm; dimensional accuracy X/Y ±0.012 mm, Z ±0.0025 mm; PLA filament; printing temperature 205 °C; print speed 50 mm/s; infill ratio 15%; tree supports.

This experiment enables designers to holistically experience both the physical and digital prototyping process, increasing decision-making speed and raising design quality in educational and professional processes.

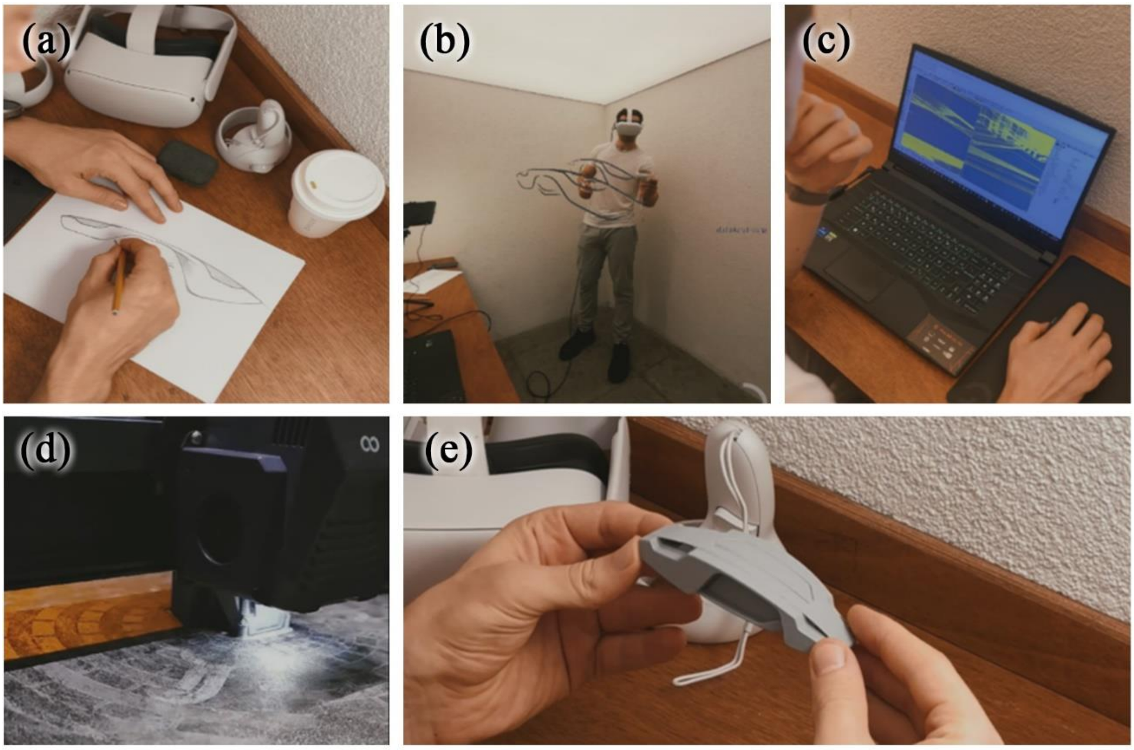

Figure 5 - Hybridization of Virtual Modeling and Physical Additive Fabrication [author's material].

Figure 5 illustrates the step-by-step design and fabrication process. The workflow begins with drawing the desired design on paper (a), followed by designing in a virtual environment using the Gravity Sketch application (b), which also includes its reflection in the virtual space. The created model is then repaired and refined in the Rhinoceros application (c), before proceeding to the 3D printing process (d). Finally, the completed physical model is produced using a 3D printer (e).

Experiment 5 - 1:1 Scale Design in VR

This study was carried out by a single architect and focused on providing a realistic and interactive VR experience during the design phase, eliminating the immediate need for physical prototypes. For the experiment, a project named Ski Snow Cabin was designed to test environmental responsiveness. Conceptualized for the Myvatn region of Iceland, the design features fluid and organic forms derived from the morphology of snow accumulation and ice formation. The interior spatial organization was developed to create a thermodynamic contrast with the exterior conditions.

The modeling process was carried out using Rhinoceros 8 software and then transferred to Unreal Engine using the "Datasmith Export" tool. This ensured that geometry, layer, and material information were accurately transferred to the scene, optimized with UV mapping and material tags. In Unreal Engine, materials were organized using the PBR (Physically Based Rendering) logic, and metallic, roughness, and normal map values were optimized. Lighting was set up to provide real-time global illumination using Lumen and ray tracing technologies, supported by HDRI and skybox for environmental details. The space was enriched with added objects, animations, and environmental elements.

For the VR experience, the Oculus Quest 2 was used and connected to the PC via a cable using Oculus Link. This connection directly transfers the computer's processing power to the HMD (Head-Mounted Display), ensuring high frame rate and low latency. The VR module was activated in Unreal Engine, enabling HMD and stereo rendering features, and user interaction was made possible with motion controllers. The target frame rate was set to 80-90 FPS, and the render resolution was optimized with the LOD (Level of Detail) system. The user navigated the scene using teleport or smooth locomotion methods, observing lights, materials, and scale in real-time. This allowed designers and students to experience the project three-dimensionally before it was even built, and to make informed design decisions.

To evaluate the impact of the VR experience on design decision-making, qualitative assessment criteria were defined, including perceived scale accuracy, material realism, lighting comprehension, and spatial depth. Iterative walkthroughs were conducted before and after lighting, material, and spatial adjustments, allowing the identification of design inconsistencies and reducing the number of required revision cycles compared to conventional 2D workflows.

Prior to the experiment, designers were generally limited to expressing their ideas through 2D drawings, static renders, or physical models; this provided limited feedback on spatial scale, the effect of light on the space, and the feel of the materials. With the VR experience, the project became explorable in real scale and three dimensions, design decisions could be tested instantly, and spatial perception and client interaction were significantly improved. Professionally, the design process was accelerated, the margin of error was reduced, and different alternatives could be simulated in a short time. Educationally, students deepened their learning experience by observing complex geometries, light-shadow play, material, and spatial scales in real-time in the VR environment **(Figure 6)**.

The technical advantages of this method are also evident. Thanks to PBR material settings in Unreal Engine, light and material interactions could be observed in real-time, and the effect of light on the space could be instantly assessed with Lumen's global illumination. A low-latency and fluid experience was provided with an 80-90 FPS target in VR mode, and user comfort was ensured with teleport and smooth locomotion methods. This process replaces design evaluation and model preparation procedures that took hours in classic methods, providing significant advantages in both time and cost. The experiment can also be used as an interactive and realistic learning tool that enhances spatial perception for students and recent graduates.

Tools and Technical Specifications Used:

MSI Laptop Pulse GL76 11UEK: Intel Core i7-11800H, 8 cores / 16 threads, boost frequency up to 4.6 GHz, 32 GB DDR4 RAM, NVIDIA RTX 3060 Laptop GPU 6 GB VRAM, NVMe SSD 1.84 TB.

Rhinoceros 8: SUBD-based modeling, creation of complex geometries, making digital models suitable for 3D printing, and correction of surface errors. The model's manifold structure can be checked and prepared for printing.

Unreal Engine: Scene transfer from Rhinoceros with Datasmith Export, PBR materials (metallic, roughness, normal map), real-time lighting and shadow simulation with Lumen global illumination, adding environmental details with HDRI and skybox, scene optimization for high FPS and low latency for the VR experience.

Oculus Quest 2: VR headset, 1832×1920 pixels/eye, 72-90 Hz refresh rate, 6 DoF motion tracking. Transfers the computer's processing power directly to the headset with Oculus Link, offering a fluid, low-latency VR experience. Integration with Gravity Sketch allows for 1:1 scale freeform modeling and scene navigation.

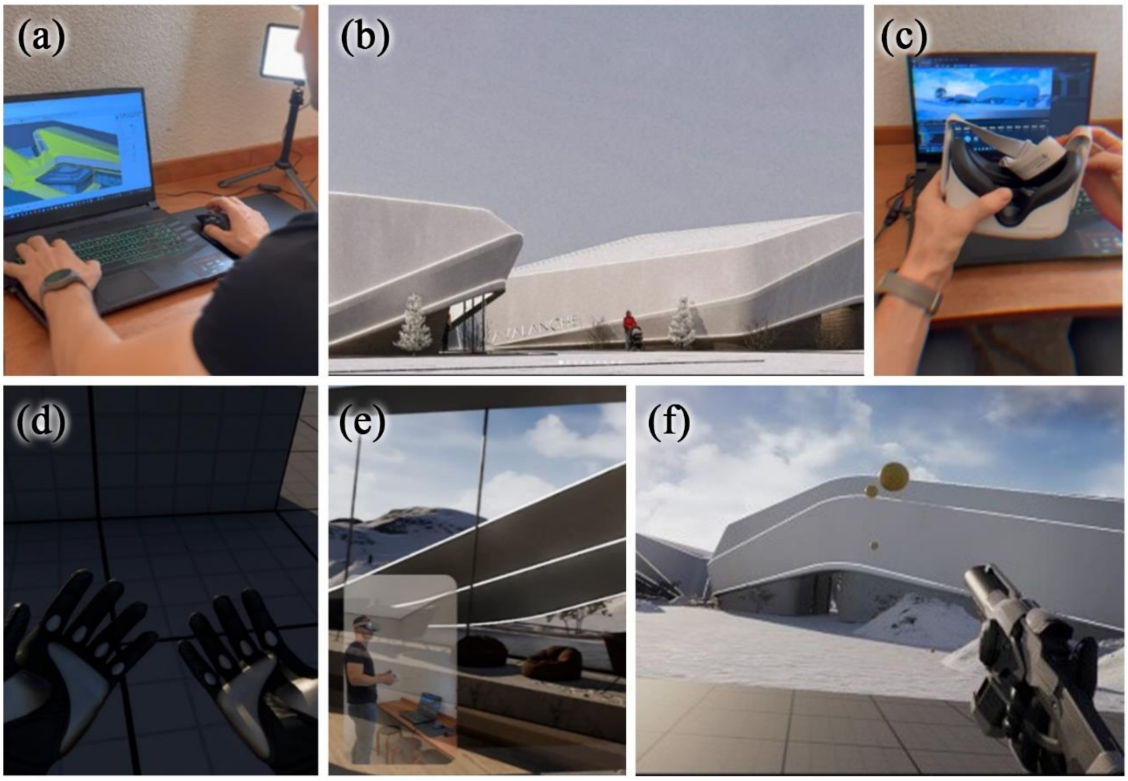

Figure 6 - 1:1 Scale Design in VR [author's material].

Figure 6 presents the project modeling and exploration process. The workflow begins with project modeling in the Rhinoceros application (a), followed by rendering the project within the same environment (b). The model is then transferred to the Unreal Engine application, where settings are configured and testing is conducted using the Oculus Quest 2 device (c). Finally, the project is explored interactively in Unreal Engine with the Oculus Quest 2, capturing various perspectives and interactions (d, e, f).

Repeatability, Reproducibility, and Technical Transparency

To ensure repeatability and reproducibility, all experimental cases were conducted using explicitly defined software environments, hardware configurations, and parameter settings. Although the study is positioned within a Research through Design framework, the experiments were structured to allow methodological replication by other researchers and practitioners.

Software environments and versions.

The primary modeling and design tools included Rhinoceros 8 (SubD and NURBS workflows), Autodesk Maya (polygonal and freeform modeling), Gravity Sketch (VR-based 1:1 modeling), Unreal Engine 5 (real-time visualization and VR evaluation), and game-engine-based simulation pipelines. AI-based visualization and generative processes were conducted using Krea AI (real-time screen-based visualization), MidJourney (Retexture and Edit modes), and LookXAi and Kling AI for animation. All experiments were executed on a workstation equipped with an Intel Core i9-13900HX CPU, 32 GB DDR5 RAM, NVIDIA RTX 4070 (16 GB VRAM), and NVMe SSD storage.

Key generative and visualization parameters.

In AI-assisted visualization workflows, generative fidelity was typically set between 80-90%, shadow softness between 0.6-0.8, reflection intensity between 0.3-0.7, and global illumination values between 70-85%, depending on the case. Prompt structures followed a consistent hierarchy: spatial configuration - material definition - lighting conditions - camera behavior. In generative retexturing experiments, RGB-coded material segmentation was applied to increase AI controllability and output consistency.

VR viewing conditions and navigation scenarios.

All immersive evaluations were conducted at a 1:1 scale using Oculus Quest 2 connected via Oculus Link. Unreal Engine 5 scenes were configured with PBR materials, Lumen global illumination, HDRI-based sky lighting, and a target frame rate of 80-90 FPS to minimize motion discomfort. Navigation scenarios included both teleport-based and smooth locomotion modes, allowing users to evaluate spatial perception, scale accuracy, and material realism under different movement conditions. Each VR session consisted of iterative walkthroughs conducted before and after lighting, material, or geometric adjustments.

Evaluation and feedback framework.

Although the study does not rely on statistical user testing, a repeatable qualitative assessment protocol was applied across cases. Evaluation criteria included perceived scale accuracy, spatial coherence, material plausibility, lighting comprehension, and ergonomic clarity. Design revisions were triggered when inconsistencies were observed during VR walkthroughs or physical prototyping stages, forming an iterative feedback loop between digital, immersive, and physical environments.

Limitations of reproducibility.

It is acknowledged that AI-based generative systems introduce probabilistic variability, meaning that identical prompts may not produce identical visual outputs. However, by maintaining consistent prompt structures, parameter ranges, and evaluation criteria, the experiments achieve methodological reproducibility at the process level rather than at the level of identical visual artifacts.

This level of technical specification allows the experiments to be replicated, adapted, or extended in different architectural contexts while preserving the core research logic and evaluative framework.

4 RESULTS AND DISCUSSION

The results are reported in a descriptive and case-specific manner, focusing on observable effects, procedural outcomes, and comparative findings. In comparison with similar studies in architectural visualization and VR-based design evaluation, the observed improvements in iteration speed, perceptual feedback, and error detection align with previous reports highlighting the benefits of hybrid digital-physical workflows, while extending these insights to post-digital architectural practice.

Results of Experiment 1: AI-Assisted Retexturing and Visual Iteration The first experiment demonstrated that AI-assisted retexturing significantly accelerated early-stage visual iteration compared to conventional rendering workflows. When RGB-based material segmentation was applied prior to AI processing, the generated outputs exhibited higher consistency in material boundaries and reduced visual noise. Comparative analysis between pre-AI and post-AI iterations showed that surface differentiation, lighting readability, and overall visual coherence improved without requiring extensive manual post-processing. The experiment also revealed that designer control increased when prompt structures followed a fixed hierarchy combining spatial description, material definition, and lighting conditions. These findings demonstrate a novel application of AI-assisted retexturing in architectural workflows, showing measurable improvements over traditional methods in terms of speed and visual clarity.

Results of Experiment 2: Generative Image Editing and Form Adaptation The second experiment focused on AI-driven image editing as a tool for form adaptation rather than form generation. The results indicated that controlled editing modes allowed existing architectural geometries to be incrementally transformed while preserving their underlying spatial logic. Iterative comparisons showed that small prompt and parameter adjustments produced measurable variations in façade articulation and surface continuity. The experiment confirmed that AI-based editing was most effective when used as a post-design refinement tool rather than as a primary form-finding mechanism. Compared to prior research emphasizing AI in early-stage generative design, these results highlight the value of AI for precision refinement and controlled adaptation, reinforcing its role as a hybrid tool in post-digital workflows.

Results of Experiment 3: Physical Prototyping via 3D Printing In the third experiment, digital models were translated into physical artifacts using additive manufacturing. The results revealed that SubD-based geometries required systematic surface closure and mesh optimization prior to export, directly affecting print success and material stability. Physical prototypes exposed geometric inconsistencies that were not immediately perceptible in screen-based environments, particularly at connection points and curvature transitions. Feedback from the printed models led to iterative digital adjustments, confirming the role of physical prototyping as a corrective and validation stage within the hybrid workflow. This confirms the scientific novelty of integrating VR, AI, and 3D printing in a continuous feedback loop, allowing architects to identify and correct errors prior to final realization.

Results of Experiment 4: Real-Time Visualization in Unreal Engine The fourth experiment examined real-time visualization as an evaluative design environment. The results showed that Unreal Engine-based visualization enabled immediate assessment of lighting behavior, material response, and spatial depth under real-time conditions. Adjustments to global illumination and material parameters produced perceptible changes in spatial atmosphere that were not fully predictable in offline rendering workflows. The experiment demonstrated that real-time visualization facilitated rapid feedback loops between design modification and perceptual evaluation, particularly during late-stage refinement. These findings provide novel evidence supporting the adoption of game-engine-based visualization as a scientific method for reducing perceptual mismatch and accelerating design decision-making.

Results of Experiment 5: 1:1 Scale Design Evaluation in Virtual Reality The final experiment evaluated architectural space at full scale using immersive virtual reality. The results indicated that scale perception, spatial proportion, and ergonomic relationships became significantly more legible in VR compared to screen-based evaluation **(Shlyakhtich & Kisselyova, 2025)**. Several design decisions related to ceiling height, circulation width, and curvature radius were revised following VR walkthroughs. The comparison between pre-VR and post-VR design states showed improved spatial clarity and reduced perceptual mismatch. The experiment confirmed VR as an effective medium for identifying spatial issues prior to physical realization. These results demonstrate the scientific novelty of applying 1:1 immersive evaluation in a structured experimental workflow and contribute empirical evidence supporting VR's effectiveness in both professional and educational settings.

Overall, the results across all five experiments reveal consistent procedural patterns: accelerated iteration, increased perceptual feedback, and iterative correction through hybrid digital, immersive, and physical environments. By systematically combining AI-assisted visualization, generative editing, VR evaluation, and physical prototyping, the experiments offer a scientifically novel approach to post-digital architecture. The findings corroborate and extend prior studies, providing empirical support for the hybridization of computational, immersive, and tangible workflows while highlighting its significance for professional practice, design pedagogy, and methodological reproducibility.

Historical Context and the Dissolution of Static Stylistic Codes

Architecture has historically evolved at the intersection of necessity and creativity. Early human shelters were primarily functional, providing protection from predators, adapting to climate, storing resources, and fulfilling ritualistic needs. Aesthetic considerations were secondary to survival. Over time, humans began to conceptualize space as a field of ideas, exploring natural geometry, light, shadow, and environmental conditions, laying the foundation for architectural thinking and the emergence of aesthetic intent. Technological advances - from arches and domes in antiquity to reinforced concrete in the modern era - enabled the development of new architectural languages, each unlocking novel morphologies and construction possibilities.

Architecture has historically evolved at the intersection of necessity and creativity. Early shelters were primarily functional, while aesthetic considerations emerged later as humans conceptualized space through geometry, light, and environmental conditions. Throughout history, architectural styles served as markers of cultural, technological, and social identity - from the mathematical order of the Renaissance to the functionalism of Modernism **(Karatseyeva et al., 2025)**. These styles emerged gradually, shaped by societal norms and material constraints **(Schumacher, 2011)**.

In the contemporary data-driven era, traditional stylistic codes have become less rigid. The speed of technological change and the availability of computational tools have blurred the boundaries of historical styles. Rather than adhering to fixed aesthetic movements, contemporary architecture increasingly prioritizes adaptive, performative, and context-specific solutions **(Abdrassilova & Aukhadiyeva, 2024)**. This shift underscores the value of designs that are not merely visually novel but are contextually aware and materially innovative **(Carpo, 2017; Schumacher, 2011)**.

From Digital to Post-Digital Architecture

The digital turn of the late 1990s and early 2000s emphasized mastery of computational tools as a measure of architectural skill. Parametric modeling, algorithmic design, and CAD-based workflows foregrounded form-making as a visible demonstration of technological capability. In digital architecture, form often served as the primary indicator of an architect's expertise, with computational processes remaining explicit and evident in the final design **(Schumacher, 2011)**.

Post-digital architecture represents a shift from this paradigm. Digital tools become omnipresent yet largely invisible, forming an ambient medium rather than standing out as explicit effects. Architectural form emerges through complex interactions among data streams, sensory inputs, material behaviors, and AI simulations, rather than solely from predefined geometric intentions. In this context, AI is a generative tool capable of producing rapid design variations, shortening rendering times, and enabling parametric or generative experimentation. However, it is the architect who provides context, intent, and critical judgment, transforming these computational outputs into meaningful, culturally aware architecture.

Micro-Languages and the Role of the Architect

Each project within post-digital architecture develops a unique micro-language - an adaptive system of rules, algorithms, and procedural tools guiding form evolution **(Hou et al., 2024; Zhang et al., 2024)**. Architecture becomes a living process, evolving in response to environmental stimuli, material feedback, and human interaction, akin to a biological organism **(Alaneme et al., 2023; Yang et al., 2021)**.

The architect's role evolves from producing fixed representations to curating a design genome, defining rules, boundaries, and interactions that govern the system. Generative algorithms enable simulation of complex behaviors under varying environmental, material, and social conditions **(Kolarević, 2003; Spiller, 2018)**. AI accelerates conceptual exploration, offering a broad spectrum of possibilities. Yet, human interpretation ensures cultural relevance, spatial coherence, and experiential meaning. This hybrid process balances computational potential with human creativity, preventing superficial or purely aesthetic-driven design outcomes **(Carpo, 2017)**.

Human-AI Collaboration: Current and Future Practices

AI has become an essential collaborator in architectural practice. Today, architects use AI to rapidly generate conceptual designs, produce multiple form variations, accelerate visualization, and optimize workflow efficiency. AI can analyze historical or cultural datasets to propose design solutions that connect past influences with contemporary contexts.

In the future, AI is expected to be further integrated into adaptive architectural systems. It will analyze user behavior and environmental data to generate responsive designs, automate material optimization for prototypes, and support the creation of live, environmentally aware structures. Coupled with VR, AR, and metaverse platforms, architects will conduct real-time, user-centered form testing, refining design decisions in both virtual and physical spaces. This trajectory positions architecture as a continuously adaptive, data and algorithm-driven process.

Ethical, Economic, and Educational Considerations

The integration of AI into architecture raises ethical and practical questions. Issues of creative authorship, copyright, and ownership of AI-generated designs require careful consideration. Economically, AI has the potential to reduce project costs and increase efficiency, reshaping professional practice.

Architectural education must evolve to prepare students for post-digital workflows. Integrating AI, VR, and AR tools into curricula equips future architects to navigate emerging technologies while maintaining critical, context-driven design thinking. By doing so, education ensures that architects remain central in shaping meaningful, culturally informed, and sustainable environments, despite the accelerating pace of digital trend cycles.

5 CONCLUSIONS

1. It was established that post-digital architecture represents a fundamental shift in architectural thinking, in which form is no longer understood as a fixed object but as an evolving system shaped by algorithms, data flows, material properties, and human intent.
2. It was demonstrated that the hybridization of digital environments, artificial intelligence, VR/AR technologies, and physical tools transforms architectural practice, positioning the architect as a curator of the "form genome" rather than the author of predefined artifacts, and enabling the creation of adaptive and interactive architectural systems.
3. The scientific and practical significance of conceptualizing architectural objects as evolutionary systems was substantiated, justifying the transition from universal stylistic languages toward localized, context-sensitive micro-languages of architectural form-making.
4. It was established that human-AI collaboration is a central component of the post-digital paradigm, wherein artificial intelligence introduces variability and generative capacity, while architects define intent, rules, evaluative criteria, and semantic meaning.
5. It was revealed that architects operating within a post-digital framework require competencies in algorithmic and generative design, immersive technologies, and adaptive system management, reflecting a shift from authorship of fixed forms to stewardship of evolving architectural processes.
6. It was shown that the integration of physical and digital workflows (phygital environments) enables the development of more accurate, adaptive, and context-responsive design solutions through continuous feedback between computational models and material realization.
7. It was established that future research should focus on integrating adaptive AI systems with live environmental data, advancing user-centered evaluation within immersive VR/AR environments, and assessing the long-term impact of hybrid digital-physical workflows on architectural practice and education.
8. It was demonstrated that post-digital architecture holds significant practical and educational relevance for post-Soviet contexts, particularly in Kazakhstan and Central Asia, where a rich architectural heritage intersects with rapid digitalization and globalized design trends.
9. It was substantiated that embedding AI-driven generative modeling, immersive VR/AR design at a 1:1 scale, and digital fabrication technologies into architectural curricula fosters the development of context-aware and technologically proficient architects capable of addressing contemporary urban and environmental challenges while respecting regional identity.

REFERENCES

1. **Schumacher, P.** (2011). *The autopoiesis of architecture. Volume I: A new framework for architecture.* Wiley. https://books.google.com
2. **Oxman, R.** (2006). Theory and design in the first digital age. *Design Studies*, 27(3), 229-265. https://doi.org/10.1016/j.destud.2005.11.002
3. **Carpo, M.** (2017). The second digital turn: *Design beyond intelligence.* MIT Press. https://doi.org/10.7551/mitpress/9976.001.0001
4. **Kolarević, B. (Ed.).** (2003). *Architecture in the digital age: Design and manufacturing.* Taylor & Francis.
5. **Spiller, N.** (2018). *Drawing architecture*. Routledge.

6. **Caetano, I., et al.** (2020). Computational design in architecture: Defining parametric, generative and algorithmic design. *Frontiers of Architectural Research*, 9(4), 567-580. https://doi.org/10.1016/j.foar.2019.12.008
7. **Gu, N.** (2021). A critical review of computational creativity in built-environment design. *Buildings*, 11(1), 29. https://doi.org/10.3390/buildings11010029
8. **Castro Peña, M. L., et al.** (2021). Artificial intelligence applied to conceptual design: A review of its use in architecture. *Automation in Construction*, 124, 103550. https://doi.org/10.1016/j.autcon.2021.103550
9. **Li, C., Zhang, T., Du, X., Zhang, Y., & Xie, H.** (2024). Generative AI models for different steps in architectural design: A literature review. *Frontiers of Architectural Research.* https://doi.org/10.1016/j.foar.2024.10.001
10. **Assimov, B.** (2025). Post-Digital Architecture: The New Genome of Form Generation. Portal about Design.
11. **Nabiyev A.S., Baitenov E.M., Issabayev G.A.** (2024) Роль цифровых технологий в развитии устойчивой архитектуры Казахстана // *Вестник КазГАСА*. 2024. Том 4 № 94. https://doi.org/10.51488/1680-080X/2024.4-07
12. **G.S. Abdrassilova, L.M. Aukhadiyeva** (2024) Приоритетные направления развития региональной архитектуры Казахстана в XXI веке // *Вестник КазГАСА*. 2024. Том 3 № 93. https://doi.org/10.51488/1680-080X/2024.3-01
13. **T.Y. Karatseyeva, A.T. Akhmedova, S.V. Ilvitskaya** (2025) Формирование стиля в жилищной архитектуре Алматы 1930-1950-х годов: поиск нового курса и проблема выбора // *Вестник КазГАСА*. 2025. Том 3 № 97. https://doi.org/10.51488/1680-080X/2025.3-02
14. **Hou, N., Nishina, D., Sugita, S., Jiang, R., Kindaichi, S., Oishi, H., & Shimizu, A.** (2024). Virtual reality space in architectural design education: Learning effect of scale feeling. *Building and Environment*, 248, 111060. https://doi.org/10.1016/j.buildenv.2023.111060
15. **Zhang, Y., et al.** (2024). Integrating extended reality (XR) in architectural design practice and education: A review. *Buildings*, 14(12), 3954. https://doi.org/10.3390/buildings14123954
16. **Schnabel, M. A.** (2025). Implementation of Virtual Reality Technology in Architecture Field and Education: A Review. *Archives of Computational Methods in Engineering*, 32, 2457-2465. https://doi.org/10.1007/s11831-025-10225-8
17. **Tostoes, A., & Ferreira, Z.** (2018). Licence to live in the Barbican Estate. In M. Melenhorst, P. Providencia, & G. Canto Moniz (Eds.), *Teaching through Design* (pp. 235-247). University of Coimbra and Hochschule Ostwestfalen-Lippe.
18. **Sandes, C. A.** (2014). Identity and heritage in the global city: The Barbican Estate and Robin Hood Gardens, London, UK. *SpringerBriefs in Archaeology*, 37-45. https://doi.org/10.1007/978-3-319-09689-6_4
19. **Ko, J., Ajibefun, J., & Yan, W.** (2023). Experiments on Generative AI Powered Parametric Modeling and BIM for Architectural Design. *preprint arXiv*.
20. **Yigitbas, E., Nowosad, A., & Engels, G.** (2023). Supporting Construction and Architectural Visualization through BIM and AR/VR: A Systematic Literature Review. *AEC/FM Industry Review (preprint on arXiv)*.
21. **Coppens, A.** (2022). Integrating Immersive Technologies for Algorithmic Design in Architecture. *preprint arXiv*.
22. **"PARAMETRIC DESIGN IN ARCHITECTURE: Algorithmic Form Generation with Grasshopper and Rhino"** (2025). *American Journal of Pedagogical and Educational Research*, 38, 23-26.
23. **"Innovative method for designing architectural plans and constructing prefabricated structural components using digital design solutions"** (2025). *Architecture Papers of the Faculty of Architecture and Design STU*, 30(3), 15-22. https://doi.org/10.2478/alfa-2025-0014

24. **A.Ujma, Y. Onichshenko, A. Akunov, D. Chingissov** (2025) 3D-печать в архитектуре Казахстана: от экспериментальных домов к устойчивым решениям // *Вестник КазГАСА*. 2025. Том 3 № 97.https://doi.org/10.51488/1680-080X/2025.3-03
25. **Alaneme, K. K., Anaele, J. U., & Oke, T. M.** (2023). Mycelium-based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications. *Construction and Building Materials*, 374, 131220. https://doi.org/10.1016/j.conbuildmat.2023.131220
26. **Yang, L., et al.** (2021). Material function of mycelium-based composite: Review and experiments. *Frontiers in Materials*, 8, 737377. https://doi.org/10.3389/fmats.2021.737377
27. **Wong, P. Y., et al.** (2024). Advances in microbial self-healing concrete: A critical review. *Science of the Total Environment*, 103456, 1-18. https://doi.org/10.1016/j.scitotenv.2024.174553
28. **Danibekova E., Abdrassilova G., Daurenbekova R., Abdullayeva N.** (2025) Современная архитектура мечетей: баланс между глобализацией и поиском региональной идентичности // *Вестник КазГАСА*. 2025. Том 2 № 96. https://doi.org/10.51488/1680-080X/2025.2-01
29. **Shlyakhtich Y., Kisselyova T.** (2025) Современные принципы организации пространств «Open Space» // *Вестник КазГАСА*. 2025. Том 2 № 96. https://doi.org/10.51488/1680-080X/2025.2-03