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www.gecekitapligi.com
gecekitapligi@gmail.com

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CONTENTS

CHAPTER 1

THE INTELLIGENT INTERIOR: MACHINE LEARNING (ML) AND ARTIFICIAL INTELLIGENCE (AI) IN MODERN DESIGN PRACTICE

İrem CEYLAN ENGİN[1]

1 Dr İrem CEYLAN ENGİN, Kocaeli Üniversitesi, Mimarlık ve Tasarım Fakültesi, İç Mimarlık, iremceylan-@hotmail.com, ORCID: 0000-0003-3761-6004.

INTRODUCTION

The discipline of interior architecture design intricately weaves together the principles of functionality and tranquillity, resulting in distinctive visual narratives that are meticulously tailored to accommodate individual inclinations and requirements. Achieving designs that are not only aesthetically delightful but also pragmatically effective necessitates a profound degree of human expertise. Interior architects are primarily concerned with tackling the functional complexities inherent in various spaces, whilst simultaneously fostering visually captivating environments (Demirarslan, 2006). The incorporation of emerging technologies has revolutionized this discipline, profoundly shaping the techniques used to design and utilize interior spaces. Since the 1990s, the impact of digital technology on interior architecture has been significant, streamlining two essential processes: the conception and realization of interior environments (Demirarslan and Demirarslan, 2020). Central to this development are advanced two-dimensional and three-dimensional computer-aided design (CAD) software tools, which have significantly improved over time as a result of swift technological advancements (Bullinger et al., 2010; Adediran et al., 2024).

Alongside advancements in two and three-dimensional CAD systems, Artificial Intelligence (AI) has emerged as a transformative digital resource within interior architecture. AI not only enhances traditional design techniques but also expands its influence into a multitude of applications that reshape functionality and aesthetics in inventive ways (Almaz et al., 2024). This integration of AI technology empowers designers and clients alike with advanced tools that elevate the creative process, enabling tailored customization and optimized spatial arrangements. The rise of Generative AI has sparked significant attention, catalyzing the generation of content from textual prompts across various modalities—including voice, text, and visual media—leading to the creation of innovative outputs such as two-dimensional visuals, videos, and three-dimensional models. Recent breakthroughs in text-to-image generation have shifted from generative adversarial networks (GANs) to cutting-edge diffusion models, renewing interest in learning-based representations that are applicable to three-dimensional design (Gao et al., 2022; Corvi et al., 2023; Yeo et al., 2023). Notable diffusion tools like BART and ChatGPT excel in text-centric functions, while Dall-E Stable Diffusion and Midjourney specialize in producing detailed visual representations stemming from written instructions and images (Lewis et al., 2019; Yeo et al., 2023; Thampanichwat et al., 2025). These diffusion models facilitate the conditioning of image generation based on both textual inputs and initial seed images, thereby permitting greater complexity and depth in the resultant outputs, which can integrate additional modalities such as video and auditory elements. With ongoing advancements in technology, AI systems are yielding invaluable insights and bolstering numerous aspects of design, ranging from conceptual mapping and documentation of cultural areas to dynamic presentations and visualizations through graphics and animation (Demirarslan and Demirarslan, 2020; Giordano et al., 2022). However, the effectiveness of these models is contingent upon access to extensive, modality-specific training datasets (Yeo et al., 2023).

Over the past two decades, the intersection of AI and design methodologies has yielded innovative frameworks that significantly enhance contemporary practices. Intelligent applications are progressively administering various systems within interior environments—including heating, ventilation, air conditioning (HVAC), smart lighting, and environmental quality—thus profoundly transforming design and construction methodologies throughout the entire project lifecycle (Golmohamadi, 2022; Samuel et al., 2022; Mobarakeh and Sayyaadi, 2023). AI's capacity for continuous learning is pivotal, particularly through the integration of supervised machine learning into AI diffusion models, (Aziz and Dowling, 2019). A remarkable advancement in this realm is the evolution of image recognition, often known as machine or computer vision, which is reshaping the landscape of design (Mohit, 2016; Hanafy, 2023). Moreover, a graph-based generative approach in machine learning is proving effective in harnessing data from established high-performance models to improve the architectural design process, particularly in both Euclidean and non-Euclidean contexts (Yin et al., 2021; Su et al., 2025). By employing machine learning algorithms in artifical intelligance technologies, scalability and adaptability enhances in managing complex networks (Yang et al., 2023). Also, machine learning in AI is paving the way for enhanced energy efficiency, sustainability, and livability in smart housing and interior design initiatives (De Silva et al., 2012; Farzaneh et al., 2021; Mahzar et al., 2023; Rajput, 2024; Arabasy et al., 2025). As a result, these advancements not only refine the precision of architectural designs but also promote greater structural cohesiveness, thereby contributing significantly to the discipline. The integration of these techniques heralds a new era of design possibilities that are both sophisticated and inherently robust.

The field of AI is currently experiencing extraordinary advancements that significantly influence a wide range of scientific disciplines. This paper aspires to delve into the innovative applications of AI within the realm of interior architectural design, concentrating specifically on the transformative capabilities of text-to-image and image-to-image generation facilitated by various AI tools. This inquiry aims to critically evaluate AI-generated designs, examining their capacity not only to augment the creative process but also to fundamentally redefine essential aspects of interior design practice. By scrutinizing AI-generated interiors through the frameworks of human ergonomics, entropy, design language coherence, and contextual appropriateness, this study seeks to offer a holistic appraisal of the role of artificial intelligence in harmonizing aesthetic allure with practical functionality in interior design. Furthermore, this paper will explore the implications of machine learning in the interior architecture science, forecasting potential future applications that could further revolutionize the field. Ultimately, this research endeavors to illuminate the transformative potential of AI in crafting environments that are not merely visually captivating but also finely tuned to enhance human experience and usability.

CASE STUDIES

This section will critically analyze case studies from the literature that employ both AI-driven diffusion techniques and machine learning in AI applications specific to interior architectural design. The discussion will delve into established criteria of interior architectural design, exploring their current and prospective implications for the discipline of architectural design. Through this examination, this paper aim to elucidate the transformative potential of these technologies within the field, questioning their efficacy and influence on contemporary design practices.

Diffusion-Based Interior Architectural Designs

In the research conducted by Chen et al. (2024), an exploration of diverse interior design concepts was undertaken utilizing text-to-image artificial intelligence diffusion models. The prompt provided for this study was: "Realistic, Chinese-style living room with a touch of modernity, featuring a sofa and a table." The diffusion models employed included DALL·E, Midjourney, and Stable Diffusion (Chen et al., 2024). The imagery produced by DALL·E 2 in Figure 1(a), presented significant discrepancies, characterized by inaccurate spatial dimensions and furniture arrangement, as well as incongruities in design language and texture. In contrast, the outputs from Midjourney demonstrated flaws related to lighting fixtures, resulting in implausible proportions and stylistic inconsistencies (Figure 1(b)). Similarly, while the images generated by Stable Diffusion maintained a resemblance of traditional Chinese design in the fixed elements, the modern elements of the furniture appeared incongruous, lacking the coherence expected from a professionally curated space (Figure 1(c)). Overall, the findings underscore the challenges inherent in employing AI-driven models for the intricate task of interior design, highlighting specific areas where these technologies diverge from established design principles.

(a) (b) (c)

Figure 1. (a) DALL-E generated; (b) Midjourney generated; (c) Stable Diffusion generated models (Chen et al., 2024).

Gan et al. (2023) employed three diffusion models—iDesigner, Stable Diffusion XL, and DALL-E—to generate interior design visuals utilizing the text-to-image methodology (see Figure 2). A uniform prompt was administered across all three models, wherein the overarching theme was the conception of hotel interiors tailored for a Nordic skiing family vacation. The prompt meticulously delineated essential features, including materials, lighting, color schemes, and texture (Gan et al., 2023). Upon evaluating the visual representation produced by iDesigner, in Figure 2 (a), it becomes evident that the design contains several ergonomic and logical inconsistencies. For instance, because of the bed fails to fully embody the Nordic aesthetic, on the wall parallel to the entrance ventilation grille is abruptly truncated, and the television is situated in a position that obstructs intended viewing angles for individuals reclining on the bed, deviating from standard hotel room ergonomics. Additionally, while spotlights illuminate the ceiling at the entrance, the main area lacks adequate lighting. Turning to the Figure 2(b) generated by Stable Diffusion XL, one of the most striking shortcomings is the misrepresentation of the Nordic design ethos. Notably, the wall behind the seating arrangement displays oversized curtains in the absence of any window openings, underscoring a fundamental confusion on the part of the AI agent. While the overall lighting achieves a dim ambience and the material textures exhibit a degree of harmony, this visual fails to capture the nuances of the intended design. Lastly, the visual crafted by DALL-E, presented at the Figure 2 (c), reveals additional design flaws, such as fabrics draping haphazardly from the ceiling and a disproportionate scale of the flooring material. Furthermore, the lighting is positioned uncomfortably low, approximately 10-15 cm above the heads of seated individuals, which could lead to discomfort and thermal issues. Although this image may initially present an appealing aesthetic to the untrained observer, a more rigorous examination reveals significant deviations from established ergonomic and design principles.

(a) (b) (c)

Figure 2. (a) iDesigner generated; (b) Stable Diffusion XL generated; (c) DALL-E 3, generated images (Gan et al., 2023).

In the study conducted by Wang et al. (2024), the authors employed artificial intelligence to generate various living environments through a diffusion model known as Room Diffusion (Figure 3). The image in Figure 3(a) illustrates the creation of a Scandinavian-style children's room, characterized by a neutral color palette dominated by pastel tones, particularly pink-beige. The input prompt provided not only specified the desired colors—pink and white—but also included a request for a distinctive pink pendant light to be suspended from the ceiling (Wang et al., 2024). Upon evaluating the design of this room, it becomes evident that the hallmark simplicity and wooden elements typical of Scandinavian aesthetics are only sparsely represented at the head of the bed. The lighting, rather than being unique, conforms to a more conventional design. Although the AI effectively recognized the pink hue within the pastel palette, it inadequately interpreted the inclusion of beige, thereby producing a space that evokes the ambiance of a teenager's room rather than embodying the imaginative essence typically associated with a children's environment. The image in Figure 3(b) corresponds to a requested Scandinavian-style kitchen. The prompt outlined specifications for light-toned walls and cabinetry painted white, complemented by black handles. Additionally, it called for an open layout that facilitates easy access to the sink and oven centrally located within the design. However, the final output reveals discrepancies; the handles are not rendered in black, and the design language lacks the quintessential Scandinavian elements. Furthermore, the lighting is insufficient, and the arrangement of the window and faucet appears unrealistic. The upper cabinets extend imperceptibly to the ceiling, devoid of any functional clearance. While the artificial intelligence demonstrates proficiency in recognizing the desired color scheme, it falters markedly in executing ergonomic principles and rendering a coherent stylistic interpretation.

(a)

(b)

Figure 3. (a) Scandinavian-style children's room generated with Room Diffusion; (b) Scandinavian-style kitchen generated with Room Diffusion (Wang et al., 2024).

In Figure 4, the interior design was conceptualized utilizing a diffusion model alongside text-to-image generation techniques. The guiding prompt for this design was ‘*’Le Corbusier's Interior Designs Mixed with Parametric Design Style*” (Yildirim, 2022). Le Corbusier's approach to interior design is rooted in modernist principles that emphasize functionality and clarity (Gans and Corbusier, 2006; McLeod, 2014). While his architectural exteriors make bold statements, his interior spaces are crafted with a focus on enhancing the quotidian aspects of daily life and promoting fluid movement within the environment. Central to his philosophy is the maxim "form follows function," wherein human necessities take precedence over mere decorative aesthetics. Upon analyzing the space depicted in Figure 4, it becomes evident that, while the fluid and organic forms characteristic of parametric design are prominently featured, there appears to be a notable neglect of the foundational principles of usability, functionality, and ergonomics inherent in Le Corbusier’s philosophy. This oversight is particularly apparent in the design of the seating elements, which, despite their aesthetic fluidity, lack adequate consideration for human ergonomics. Additionally, an examination of the window design reveals an excessive number of partitions relative to the ceiling height, suggesting a divergence from realistic architectural representation by artificial intelligence. Furthermore, the absence of integrated ceiling lighting points to a further disregard for the practical necessities of spatial illumination in design.

Figure 4. Le Corbusier and parametric design styles generated with diffusion tools (Yildirim, 2022).

In the study of Ploennigs and Berger (2023), the interior space conceptualized as a cozy living room, was generated using the Midjourney diffusion tool (Figure 5.). Specific attributes, such as wood paneling, sofa dimensions, lighting conditions, and realistic rendering were meticulously articulated in the prompts provided to the AI, which subsequently generated a image (Ploennigs and Berger, 2023). Analyzing the visuals reveals that the artificial intelligence strategically positions the seating arrangement as the cornerstone of the 'cozy living room' design ethos. The utilization of soft lighting, harmonious color palettes, and varied textures serves to enhance the perception of a warm and inviting atmosphere. However, discrepancies arise in the Figure 5 (a), where the absence of a legitimate lighting source results in an artificial glare on the wooden paneling, undermining the intended realism. Additionally, the curtains appear to emanate directly from the window frame, which presents an unconventional implementation not typically encountered in professional design. Conversely, the image on the Figure 5(b) evokes a sense of detachment from reality, particularly owing to the misproportioned material textures. Collectively, these designs diverge significantly from the established aesthetic principles that characterize a professional interior designer's vision of a cozy living room.

(a) (b)

Figure 5. Midjourney generated cozy living room alternatives (Ploennigs and Berger, 2023).

The design of the cozy living room, as investigated in the study by Ploennigs and Berger (2023), was generated using advanced artificial intelligence tools, specifically DALL-E and Stable Diffusion. In Figure 6, the spatial representation created with the DALL-E model illustrates the challenges this AI encounters in accurately interpreting the nuances of realism as stipulated in the input prompt. Conversely, Figure 7 depicts the environment rendered through Stable Diffusion, which closely resembles a realistic depiction, although it notably lacks adequate ceiling lighting. An analysis of the outputs yielded by three distinct artificial intelligence models in response to the identical prompt reveals that the most satisfactory results are achieved with Stable Diffusion, highlighting its superior capability in delivering lifelike representations.

(a) (b)

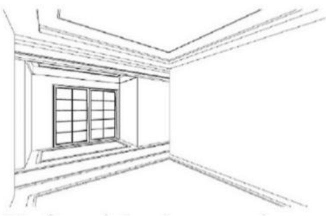
Figure 6. DALL-E generated cozy living room alternatives (Ploennigs and Berger, 2023).

(a) (b)

Figure 7. Stable diffusion generated cozy living room alternatives (Ploennigs and Berger, 2023).

In the study conducted by Chen et al. (2025), the visual representation of a living space was synthesized using a diffusion model that integrated both prompt and image-to-image generation methodologies. The prompts utilized in this study included descriptors such as "Chinese style living room," "photographic," "realistic," and "high definition," alongside an input image depicted on the Figure 8 (a) (Chen et al., 2025). Although the resultant image in Figure 8(b) initially conveys a semblance of realism, it is characterized by deficiencies in structural integrity and ergonomic principles. Noteworthy discrepancies emerge, particularly concerning the heights of the seating arrangements and the alignment between the window frames and sashes.

(a) (b)

Figure 8. (a) input image; (b) generated image of the living room (Chen et al., 2025).

In the research conducted by Albaghajati et al. (2023), the integration of sketches as input to the Midjourney diffusion model facilitated the generation of highly realistic spatial visualizations (Albaghajati et al., 2023). As illustrated in Figure 9(a), which depicts the kitchen area, the AI demonstrated its capacity to incorporate the specified flooring and countertop materials from the sketch. Nevertheless, rather than faithfully rendering the upper windows at a precise 45-degree angle, the model interpreted them as a roof interruption. Additionally, the positioning of the lighting apparatus was altered, and variations were introduced in the design and material of the stools. Although Midjourney did not produce an exact replication of the original sketch, the resulting spatial design can nonetheless be regarded as a commendable interpretation. In examining Figure 9(b), which represents the bathroom area, it becomes evident that the AI agent made significant modifications to the depicted forms. The elements of the mirror, window panes, and bathtub diverged from their respective representations in the sketch. Furthermore, discrepancies were noted in the overall structure of the building. Despite these alterations, the rendered image reflects a high degree of realism and aesthetic appeal, which can be attributed to the intricately detailed and meticulously crafted sketch provided as input. This suggests that the quality of input significantly influences the efficacy of AI in generating compelling space designs.

(a) (b)

Figure 9. (a) Midjourney generated kitchen model; (b) Midjourney generated bathroom model (Albaghajati et al., 2023)

AI and Machine Learning in Interior Architecture

In the exploration of machine learning applications within artificial intelligence for interior architecture, a multitude of studies have emerged that significantly contribute to the discourse. Notably, Chen et al. (2024) introduced an Advanced Interior Design Diffusion Model (AIDDM), which harnesses a comprehensive dataset comprising over 20,000 indoor design images. This sophisticated aesthetic diffusion model adeptly generates visually compelling interior designs predicated on textual descriptions, thereby allowing for the selection of diverse decorative styles and spatial functionalities. Their innovative approach not only renders aesthetically pleasing design alternatives for practitioners but also facilitates an expeditious regeneration of design solutions through the modification of textual prompts (Chen et al., 2024). This capability empowers designers to craft more nuanced and realistic interiors, thereby augmenting the creative process. Given the limitations of contemporary AI tools in consistently producing satisfactory design outcomes, the implications of their research are profound for advancing the intersection of machine learning and artificial intelligence in design. In a related investigation, Chen et al. (2023) unveiled a groundbreaking AI methodology for generative architectural design that produces outputs with distinct stylistic attributes and high-quality characteristics akin to those of esteemed master architects. This approach employs a diffusion model driven by textual prompts that delineate design requirements, resulting in outputs that surpass the efficacy of existing AI diffusion frameworks (Chen et al., 2023). Furthermore, in their 2025 study, Chen et al. focused on the derivation of designs from images of interior structures, intentionally omitting existing furniture rather than merely substituting it. Their findings demonstrate that this innovative design paradigm, when integrated with the advanced methodology, achieves near-instantaneous design generation and modification, significantly enhancing creativity and efficiency within the design process (Chen et al., 2025). The enhancement is particularly evident when analyzing the generated images, which exhibit remarkable detail, structural integrity, and adherence to fundamental spatial criteria such as ergonomics, material selection, and lighting (see Figure 10). Nevertheless, the research indicates there remains potential for further refinement in visual realism, underscoring the ongoing evolution in this domain.

Figure 10. Realistic interior design image generation *(Chen et al., 2025).*

Yang et al. (2024) introduced DiffDesign, an innovative controllable diffusion model that harnesses meta priors to facilitate the generation of well organized interior designs. This model is underpinned by generative priors derived from a two-dimensional diffusion framework, pre-trained on an extensive dataset of images, which serves as its rendering foundation (Yang et al., 2024). Figure 11 presents the spatial design conceptualized by DiffDesign. The visual representation highlights an array of lighting solutions, including integrated illumination within shelving units, beneath the bar counter, and throughout the overall space. The bar stools have been ergonomically designed, ensuring that users can comfortably rest their feet on both the stools and the bar's footrest. The flooring is constructed from two distinct materials, elegantly separated by a transition bar, which enhances the visual depth and adheres to established interior design principles.

Figure 11. Realistic bar design generation with DiffDesign (Yang et al., 2024).

Qin et al. (2024) applied ControlNet's cutting-edge technology to network management to advance the generation of interior designs, effectively merging machine learning algorithms with a decentralized architectural framework. This methodology has demonstrably improved performance and security of the network (Qin, 2024). Figure 12 illustrates the spatial design emerging from their research. Although the textures of materials and the lighting exhibit a high degree of realism, certain design elements, such as the non-functional curtains, exhibit impracticality. Moreover, the alignment of the coffee table to the armchair appears to be misaligned, raising concerns regarding spatial coherence and functional design integrity.

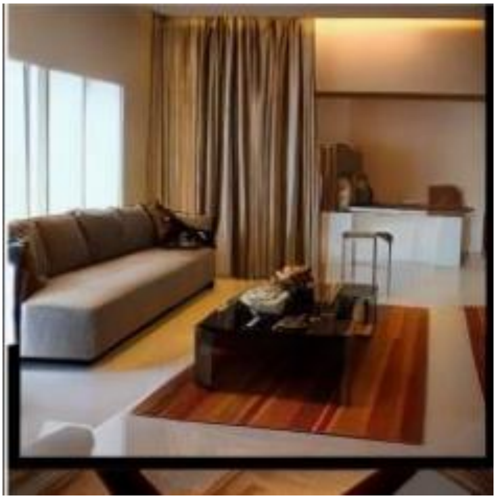


Figure 12. Living room generation with ControlNet (Qin, 2024).

Yilmazer et al. (2019) explored the application of machine learning within the realm of artificial intelligence, focusing not on the initial stages of space design but rather on the continuum from design to development. Their research harnesses machine learning to anticipate human auditory perceptions in indoor environments (Yilmazer et al., 2019). This underscores the undeniable role of machine learning as a critical input within artificial intelligence, particularly in enhancing spatial design.

In a complementary study, Taheri and Rasoolzadeh (2025) investigated agent-based systems and their efficacy in augmenting the capabilities of AI tools in interior architecture. Their findings illuminate the fundamental importance of these systems in optimizing the efficiency of artificial intelligence applications throughout the interior design process. Furthermore, the implications of their work are pronounced in the context of cultivating healthy buildings, as it elucidates the intricate relationship between sustainable materials and occupant wellbeing (Taheri and Rasoolzadeh, 2025). Amidst the backdrop of recent environmental crises, sustainability and environmentally conscious practices have garnered heightened attention in global discourse (Lanyi, 2008; Ceylan, 2024). Consequently, the capacity of machine learning, embedded within the framework of artificial intelligence, to identify and advocate for the use of eco-friendly materials is paramount in addressing the pressing challenges faced in contemporary design. This innovative integration not only aligns with the urgent need for sustainable practices but also contributes to a more profound understanding of the intersection between design, technology, and environmental stewardship.

CONCLUSION

The advent of artificial intelligence, particularly through the deployment of diffusion models, has emerged as a transformative digital resource in the domain of interior architecture. This article critically examined interior architectural design images generated through AI and machine learning, evaluating these outputs against established interior design criteria, including ergonomics, entropy, conceptual coherence, aesthetics, materiality, color theory, texture, and lighting design.

From an ergonomic standpoint, the generated interiors exhibit notable shortcomings; for instance, designs produced with iDesigner fail to accurately configure optimal TV viewing angles and distances that align with anthropometric standards. Similarly, Room Diffusion notably deviates from fundamental ergonomic principles in its design execution. Conceptually, the output from Stable Diffusion XL reveals a significant misalignment with the core tenets of Nordic design, while Room Diffusion lacks a coherent stylistic interpretation. Observations of imagery generated by Midjourney indicate that the model misinterprets architectural elements, such as rendering upper windows inaccurately as interruptions in the roofline rather than adhering to the correct 45-degree angle. In terms of lighting, AI-generated spaces using iDesigner display a discrepancy in lighting height that does not conform to human anthropometric needs. Conversely, images produced with DALL-E feature lighting positioned uncomfortably low—approximately 10 to 15 centimeters above the heads of seated individuals—potentially leading to discomfort and adverse thermal conditions. Furthermore, Midjourney-generated designs often suffer from the lack of a legitimate light source, resulting in unnatural glare on wooden paneling that detracts from the intended realism. Similarly, certain images produced by Stable Diffusion demonstrate inadequate ceiling lighting. Regarding materiality and color application, outputs from DALL-E reveal discrepancies in the proportionality of flooring materials, while Room Diffusion presents inconsistencies by incorporating either divergent colors or materials not specified in the initial prompts. Midjourney's imagery often evokes a sensation of detachment from reality, primarily due to misproportioned material textures, with instances where disparate materials are included in the final composition despite adherence to a guiding sketch during the image-to-image generation process. Moreover, logical inconsistencies manifest in the form of design elements lacking realism; for example, the iDesigner model occasionally includes curtains in windowless sections, undermining both aesthetic integrity and functional relevance, while DALL-E suffers from inaccuracies in spatial dimensions and furniture arrangement.

Examining the impact of machine learning on AI diffusion models reveals that the Advanced Interior Design Diffusion Model (AIDDM) holds significant potential for augmenting designers' ability to create more nuanced and realistic interiors, thereby enriching the creative process. When integrated with advanced methodologies, machine learning fosters a novel design paradigm characterized by rapid generation and modification of designs, which enhances overall creativity and efficiency. This advancement is evidenced by the portrayal of materials, adherence to ergonomic standards, and other fundamental spatial criteria such as effective lighting. Furthermore, the capacity of machine learning to identify and prioritize eco-friendly materials is crucial in addressing the pressing challenges faced by contemporary design practices.

Consequently, while the current application of AI diffusion models in interior design may not yield the desired professional outcomes, these tools nonetheless provide valuable insights for amateur users. Promising advancements in machine learning applications within artificial intelligence suggest that the future of interior architectural design will involve increasingly professional examples, offering vital support to designers in their creative endeavors.

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CHAPTER 2

BIOMIMICRY IN 3D PRINTED FURNITURE: THE FUTURE OF DESIGN

İrem CEYLAN ENGİN[1]

1 Dr İrem CEYLAN ENGİN, Kocaeli Üniversitesi, Mimarlık ve Tasarım Fakültesi, İç Mimarlık, iremceylan-@hotmail.com, ORCID: 0000-0003-3761-6004.

Introduction

Biomimicry represents a dynamic and progressive field of research that seeks to address design challenges through the emulation of natural models, systems, and elements. Coined by Janine M. Benyus in 1997, the term derives from the Greek words ‘bios’ (meaning ‘life’) and ‘mimesis’ (denoting imitation). In the realm of nature-inspired design, various terminologies such as biomimetics, bio-inspired design, and biologically grounded innovation are frequently employed (Benyus, 1997, Speck and Speck, 2008; Pawlyn, 2011; Verbrugghe et al., 2023). The intersection of biomimicry and architecture manifests prominently in the works of eminent architects including Antoni Gaudí, Frei Otto, and Zaha Hadid. For instance, Gaudí revered the inherent curves of botanical life, the intricate branching of arboreal structures, and the forms found in the animal kingdom, appreciating their aesthetic and structural integrity. His masterful edifices, exemplified by La Sagrada Família and Casa Batlló, embody designs that closely mimic natural forms. Conversely, Zaha Hadid harnessed parametric design tools to conceive dynamic structures that mirror the fluidity and complexity intrinsic to the natural world.

When scrutinizing the influence of biomimicry on interior architecture and furniture design, several exemplary instances stand out. The furniture creations of Joseph Walsh, including 'enignum' and 'erosion', showcase slender layers of wood that evoke the swirling, shell-like forms, reminiscent of organic movement and growth patterns found in nature. Neri Oxman integrates biological principles with digital design methodologies in her installations such as Silk Pavilion (Fig. 1(a)) (Oxman, 2015), while Zaha Hadid’s 'Z-Chair' and 'Mesa Table' are inspired by the natural fluid dynamics and skeletal architectures. Additionally, Ross Lovegrove's designs, encompassing the 'Go Chair', 'Supernatural Chair', and 'Bone Chair' (Fig. 1(b)), are intricately influenced by natural growth patterns and cellular structures (Rodgers, 2011). Alvar Aalto’s 'Paimio Chair' and 'Tea Trolley 901' also reflect organic forms and postures observed in nature, while Joris Laarman's Bone Furniture Series employs algorithms grounded in the bird bones to optimize material utilization while ensuring structural integrity (Giovannini, 2017).

(a) (b)

Figure 1. (a) Silk Pavilion by Oxman (Oxman, 2015); (b) Joris Laarman Lab's Bone Chairs (Giovannini, 2017).

The integration of insights derived from natural systems has long been pivotal for designers; however, the inherent complexity of these systems presents substantial challenges when attempting to replicate them using conventional technologies (Chaturvedi et al., 2022). Nature's intricate structures frequently exceed the capacities of traditional design and manufacturing methodologies, thereby hindering the advancement and practical application of biomimetic research within engineering disciplines. Nevertheless, the emergence of 3D printing technology has introduced unprecedented opportunities for the fabrication of intricate, multi-scale, multi-material, and multifunctional structures that closely mirror the complexity inherent in natural systems (Yang et al., 2018; Agrawal et al., 2020). This transformative technology offers unparalleled design freedom, enabling the realization of complex geometries that are otherwise exceedingly challenging to achieve through conventional manufacturing processes. Consequently, 3D printing aligns seamlessly with the principles of biomimicry, augmenting both the functional and aesthetic dimensions of 3D-printed elements. The domain of furniture design has increasingly become a fertile ground for experimentation with diverse forms and functionalities. Contemporary designers are harnessing innovative approaches to create furniture that transcends the constraints imposed by traditional manufacturing methods. Notably, the advent of 3D printing technology has facilitated the production of consumer-specific, personalized furniture that was largely unattainable in the past (Petrova, 2024; Felek, 2020). This method not only enables the creation of uniquely tailored designs, including those inspired by biomimicry, but also challenges conventional forms of furniture through its distinctive production capabilities.

The integration of 3D printing within the framework of biomimicry in interior design provides substantial advantages: it enhances design flexibility, accelerates product development timelines, and reduces production costs while alleviating the intricacies associated with global logistics of both raw materials and finished products. Although 3D printing, originally pioneered in 1984, has long been employed within the design community for rapid prototyping and conceptual modeling, recent technological advancements now empower designers to employ 3D printers for the fabrication of completed items, ranging from lighting fixtures to tables, chairs, and various elements of interior design (Saad, 2016). Furthermore, the integration of a computer-aided design (CAD) framework with automated manufacturing processes, such as 3D printing, allows for the meticulous fabrication of components that can serve as standalone products or as integral components within more complex assemblies (Majewski, 2011). This convergence of technologies heralds the advent of a transformative paradigm in furniture design, where the intersection of creativity and operational efficiency is actualized. This paper will critically investigate the implications of 3D printing technology on biomimicry-inspired furniture within the realm of interior design, with a focus on production methodologies, material selection, and the design lexicon derived from natural inspirations. Moreover, it will explore the extent to which these innovative forms transcend the design limitations traditionally imposed by conventional manufacturing techniques.

3D Printing

Additive Manufacturing (AM), more commonly known as 3D printing, stands at the forefront of emerging technologies within the manufacturing sector. This technological evolution is enhanced by automation, robotics, advanced design techniques, and the Internet of Things (IoT) (Pandolfo, 2016). The concept of AM was pioneered by Charles Hull through a technique called stereolithography (SLA), which has since evolved to include various methods such as powder bed fusion, fused deposition modeling (FDM), selective laser sintering (SLS), inkjet printing, contour crafting (CC), direct energy deposition (DED), and laminated object manufacturing (LOM) (Ngo et al., 2018). In SLA, a 3D object is made by solidifying liquid resin through photopolymerization. A laser targets specific depths in the resin vat, causing layer-by-layer solidification until the object is completed (Melchelz et al., 2010). In powder bed fusion, thin layers of powder are spread on a build plate, and an energy source like a laser or electron beam melts the powder at specific areas based on the model of the intended shape (King et al., 2015). In FDM, molten filament extruded and formed to build new shapes (Kristiawan et al., 2021). In SLS, powder particles bind together with a laser and formed into the 3D object (Fina et al., 2017). In the inkjet method, a stable ceramic suspension, like zirconium oxide in water, is sprayed as droplets onto a substrate. Directed Energy Deposition (DED) uses a laser or electron beam to focus on a specific area, melting feedstock material (powder or wire) that fuses with the substrate before solidifying as the beam moves. Laminated Object Manufacturing (LOM) cuts and laminates layers from sheets or rolls of material (Ngo et al., 2018). The AM process involves the layer-by-layer deposition of material to construct 3D objects, signifying a fundamental shift from traditional subtractive manufacturing approaches that involve cutting, shaping, and assembling materials (Conner et al. 2014).

AM reduces waste by minimizing workstations needed, requiring only a computer for design and a 3D printer for production. This technology allows for rapid completion of products within hours, although surface finishing may take longer based on quality requirements (Gibson, 2010). Compared to traditional manufacturing, 3D printing can decrease production time by nearly 70%, labor costs by around 80%, raw material use by 70%, and waste by 60% (Marjinissen and Van Der Zee, 2017; Siddika et al., 2020). In furniture manufacturing, AM offers benefits like reduced mold opening times, streamlined processes, and efficient material use, enabling the creation of intricate, high-quality pieces in smaller batches without complex mechanical components. Designers can realize their visions more easily, while manufacturers can work with various materials, transforming traditional furniture design (Yang and Du, 2022).

In the AM workflow, a virtual 3D design is generated using Computer-Aided Design (CAD) software in the STereoLithography (STL) format, imported into a slicer program to set printing parameters, saved in G-code format, and transferred to the 3d printer device to be produced layer by layer (Ceylan Engin et al., 2025). There are three main approaches to creating a virtual 3D model of furniture for 3D printing. The first method employs traditional computer modeling software like AutoCAD, Maya, 3DS MAX, and Rhino3D. The second method makes use of parametric design software, including Pro/Engineer, UGNX, CATIA, and Solidworks, which facilitates intelligent design through the establishment of constraint relationships, enabling standardized furniture tailored to user requirements. Lastly, existing furniture can be replicated by scanning with 3D scanners, which then use software to convert the data into a triangular mesh model for quick duplication of existing designs (Yang and Du, 2022). Recently, the application of 3D printing in furniture production has been rapidly expanding. This growth reflects a significant shift towards innovative manufacturing techniques that are revolutionizing design possibilities and production efficiencies in the furniture industry (Santos et al., 2006; Aydin, 2015).

Biomimicry in Furnitures Created with 3D Printing

The Trabecula bench is an innovative seating solution that measures nearly two meters in length and is fabricated using selective laser sintering (SLS) technology in conjunction with glass-filled polyamide material (Fig. 2). This bench features a unique design characterized by its seven support legs and a lace-like surface structure. This intricate design is not only aesthetically pleasing but also lightweight, while simultaneously providing exceptional structural integrity—drawing inspiration from the biomimetic architecture of avian bones (Aydin, 2015). The legs of the bench are seamlessly integrated into the tabletop, mirroring the connectivity of trabecular bone tissue within skeletal structures, which contributes to the overall strength and stability of the piece. The complex, lace-like forms are made possible through advanced additive manufacturing techniques afforded by 3D printing. Unlike traditional manufacturing methods, 3D printing allows for the realization of such elaborate designs, ushering in a novel and futuristic perspective in the realm of interior design.

(a) (b)

Figure 2. (a) Lace-like Trabecula bench (Aydin, 2015). (b) Trabecular bone tissue (URL-1).

Lily Light, depicted in Figure 3, is a pioneering lighting product fabricated through the selective laser sintering (SLS) 3D printing technique using polyamide powder. As the first commercially viable 3D-printed lamp, Lily Light embodies an aesthetic reminiscent of the water lily flower. This innovative design is produced as a singular entity, characterized by an array of exquisitely thin and ethereal petals. Upon activation, the internal light source illuminates these petals, accentuating the intricate layering of the polymer material utilized in its construction (Hobson, 2016). The design's lightweight yet robust structural composition mirrors the venation systems observed in plants, which are essential for nutrient transport and structural fortitude. Furthermore, the Waterlily's intrinsic capability to purify water serves as a compelling metaphor within the design, symbolizing the act of illuminating space.

(a) (b)

Figure 3. (a) Lily Light (Hobson, 2016); (b) Waterlily flower (URL-2).

In the 'Sofa so Good' Project (Fig. 4), a 1.5-meter seating element was fabricated utilizing the Stereo Lithography Apparatus (SLA) method. The design ethos draws inspiration from the structural configurations found in spider webs and silkworm cocoons. A meticulous approach involved the production of a mesh design using 2.5 liters of resin material, enhanced through advanced computational software to formulate a geometric diamond mesh. This mesh was meticulously designed to be adaptable and can be refined into the sinuous contours of the seating apparatus. Subsequent to the primary fabrication, a layer of copper and chrome plating was applied to achieve the desired aesthetic finish while maintaining the overall lightweight nature of the design (Howarth, 2015). In the design, fluid forms are created with meshes that embody principles of biomimicry in architecture. The mesh configuration was optimized to ensure maximum structural integrity while employing minimal material, thereby emulating the efficient layouts of natural constructs such as spider webs and silkworm cocoons.

(a) (b) (c)

Figure 4. (a) The Sofa So Good (Howarth, 2015); (b) Spiderweb (URL-3); (c) Silkworm cacoons (URL-4).

Figure 5 illustrates the stool crafted through the FDM technique. The stool's frame is constructed using PETG, while the fabric components are woven from carbon fiber and jute fibers. This design draws inspiration from the intricate structure of bovine bones, Voronoi tessellations, and traditional drum forms, establishing a connection between textiles and the stool's frame. The alignment of beams and Voronoi cells is meticulously engineered to optimize weight distribution. Moreover, the integration of fabric with the frame is conceptually influenced by the darbuka. The frame features strategically placed openings on the bottom and sidewalls; these bottom openings facilitate the attachment of the warp and weft threads to the frame through knotting techniques. The fibers traversing the Voronoi cells to connect with the base of the frame emulate the rods found within nanoscale trabecular structures (Evrim, 2020). This design harmonizes natural forms by intertwining non-linear analogies derived from bovine skeletal structures and Voronoi cell geometries, effectively applying the principles of biomimicry throughout the creation process.

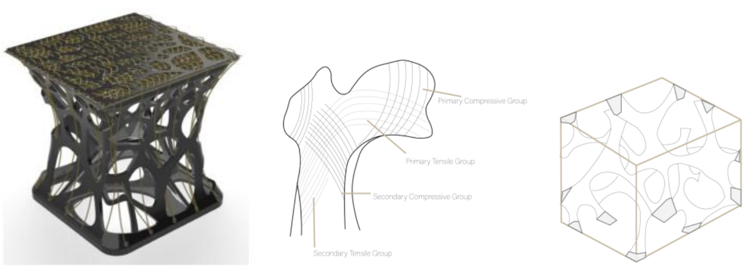


Figure 5. Left to right: Stool, trabecular alignment and trabecular geometry (Evrim, 2020).

The 3D-printed Soft Seating in Figure 6 is conceptualized as a sophisticated alternative to traditional upholstered furniture, which typically necessitates the integration of multiple materials and intricate manufacturing processes for the frame, padding, and coverings. Drawing inspiration from the structural and functional properties of plant cells, this design exemplifies the principles of biomimicry, showcasing a remarkable ability to fulfill diverse roles within a singular framework. Fabricated from polyamide, the configuration of this seating adapts its behavior based on the spatial distribution of the material, thereby allowing certain regions to exhibit softness while others maintain rigidity (Griffiths, 2014). By strategically reducing material density, more flexible seating zones can be achieved, while concentrating material in specific areas can enhance structural integrity. The chair's form was meticulously crafted through advanced 3D computer modeling software, reflecting a methodical approach to design. Upon examination of the seating framework, it is evident that the application of biomimicry principles has been executed in a manner that is fully attuned to human ergonomics. This innovation represents a compelling illustration of the capabilities of 3D printing technology in the production of complex geometrical forms, thereby pushing the boundaries of contemporary furniture design.

(a)

(b)

(c)

Figure 6. (a) Soft Seating element (Griffiths, 2014); (b) Plant cells (URL-5); (c) Plant cell structure (URL-6).

The Seat Slug represents a biomorphic reinterpretation of conventional seating, drawing inspiration from the marine organism Flabellina goddardi (sea slugs) and the intricate infinite tessellations characteristic of Japanese karakusa patterns (Fig. 7). This innovative piece is comprised of 230 distinct rapid-manufactured components necessitating assembly. Fabricated using Layered Object Manufacturing (LOM) technology, the Seat Slug employs a cement polymer material (Saad, 2016). The design is meticulously crafted to align with human ergonomic standards, ensuring user comfort. Its unique material composition and amorphous form confer several practical advantages; the structure is resilient to various outdoor environmental conditions, effectively repels water due to its beveled design, and is poised for use as versatile urban furniture.

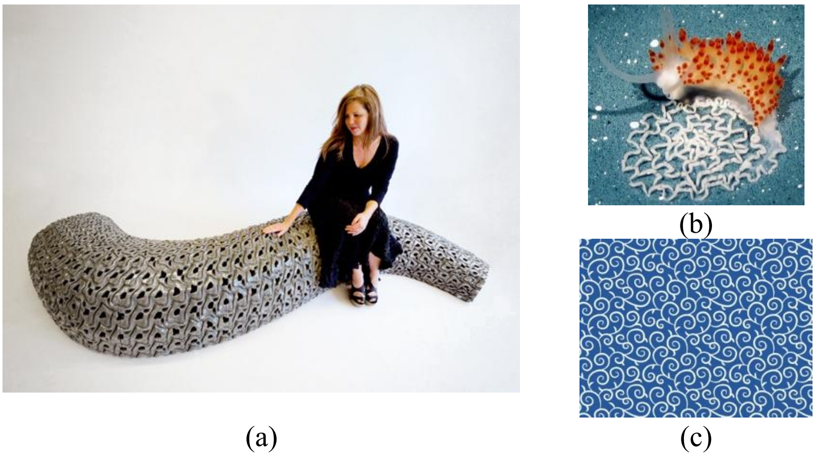


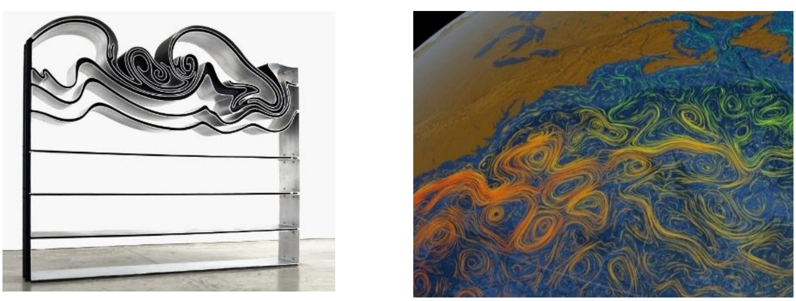
Figure 7. (a) The Seat Slug (URL-7); (b) Flabellina goddardi (URL-8); (c) Japanese karakusa patterns (URL-9).

The 3D printed organic side table, as depicted in Figure 8, exemplifies innovative design utilizing the Fused Deposition Modeling (FDM) technique. This contemporary organic form was meticulously modeled using Rhinoceros software. The construction employs a composite of date palm fronds and recycled Polyethylene terephthalate (PET) filaments developed by Elessawy et al. (2024) (Elessawy et al., 2024). From a biomimicry perspective in architecture, the design of the side table mirrors the intricate structure of cancellous (spongy) bone tissue found at the epiphyses of long bones, such as the femur. The organic lattice geometry, characterized by interwoven struts, emulates the natural load-distribution patterns inherent in biological skeletal systems. This structural efficiency is reminiscent of the adaptive processes through which bones remodel in response to mechanical stresses. Moreover, the tapered waist of the design symbolizes an evolutionary adaptation, akin to biological structures that optimize material use while ensuring structural robustness and integrity.

(a) (b)

Figure 8. (a) 3D printed side table (Elessawy et al., 2024); (b) Cancellous bone tissue (URL-10).

The Vortex Bookshelf Multiple (Fig. 9) embodies a sophisticated interplay of form and function, characterized by meticulously designed layers of perforated aluminum contours that are meticulously assembled according to a digital blueprint. This innovative bookshelf is fabricated through advanced robotic 3D printing techniques, in conjunction with the lamination of thin aluminum sheets. The design leverages parametric modeling, enabling the realization of varied configurations and patterns (JorisLaarman, 2014). The concept of biomimicry is prominently reflected in the design, drawing inspiration from the dynamic and turbulent nature of whirlpools in the sea, which are effectively captured in a state of suspension and materialized as a tangible object. Moreover, the cold texture of the utilized material accentuates this intrinsic chaos, further enriching the overall aesthetic and conceptual depth of the design.



(a) (b)

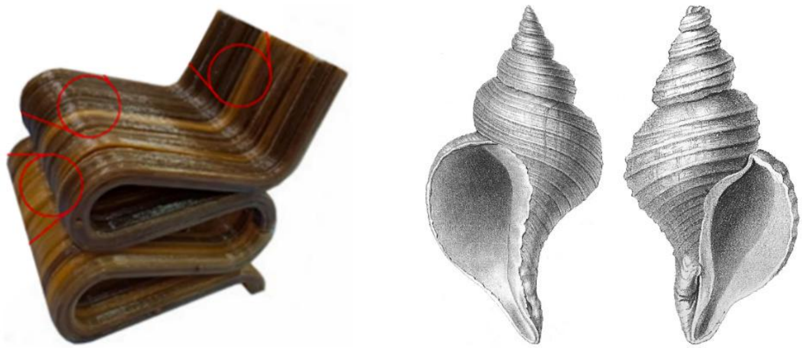
Figure 9. (a) The Vortex Bookshelf Multiple (JorisLaarman, 2014); (b) Vortex view from the satellite (URL-11).

The urban furniture depicted in Figure 10 were fabricated using the Fused Deposition Modeling (FDM) technique, employing reprocessable materials derived from recycled plastic waste (URL-12). In the context of biomimicry, the design prominently incorporates analogues of the muscle and tendon structures found within human anatomy. This biomimetic approach evokes a sense of perpetual dynamism and vitality within the urban landscape, suggesting that the city possesses an energetic and continuously evolving character.

(a) (b)

Figure 10. (a) 3D printed urban furniture (URL-12); (b) Muscles and tendons (URL-13).

The seating element depicted in Figure 11 was created using a parawood powder and PLA composite material through screw-extrusion 3D printing technology. While this design could have been accomplished using methods such as injection molding or thermofoaming, 3D printing offered distinct advantages. Notably, the chair produced demonstrated greater structural strength compared to typical plastic chairs on the market. This enhanced strength can be attributed to the thicker and more substantial material used in its construction. However, the benefits of 3D-printed items, as shown by this study's findings, go beyond just strength (Suvanjumrat et al., 2024). From a biomimicry perspective, the design encapsulates the principle of "form following function," thereby offering a multilayered approach to ergonomic considerations while resonating with naturally occurring structural patterns. The chair's smooth, undulating curves and layered architecture evoke biological forms, particularly those observed in flora and invertebrate species, such as the intricate structures of seashells and mollusk shells. This resemblance is particularly indicative of the developmental processes these shells undergo. Just as natural shells provide both support and protection, the geometry of this chair synthesizes comfort with structural stability, thereby advancing the dialogue on sustainable and innovative design practices within the field of furniture manufacturing.



(a) (b)

Figure 11. (a) The curved seating element (Suvanjumrat et al., 2024); (b) Gastropod Shell (URL-14).

The Rise Chair has been fabricated utilizing advanced pellet-extruder robotic arms, employing non-toxic polylactic acid (PLA) as the primary material (Fig. 12) (URL-15). From a biomimetic perspective, the design of the seating element embodies the metaphor of a blooming flower. Its overall form radiates both upward and outward, emulating the unfurling of petals. Furthermore, the gradient transition from turquoise at the base to a transparent finish enhances the illusion of organic growth, akin to the emergence of aquatic flora or the intricate structures of coral ecosystems. This thoughtful integration of natural aesthetics not only elevates the visual appeal but also contributes to a deeper conceptual alignment with the principles of sustainable design.

(a) (b)

Figure 12. (a) The Rise Chair (URL-15); (b) Blooming aquatic flower (URL-16).

Conclusion

The intrinsic human desire to harmonize with nature gives rise to the concept of biomimicry, which involves emulating nature in the design of man-made products for everyday environments. One of the most significant applications of biomimicry in interior architecture design can be seen in furniture design. This paper explored innovative furniture crafted through 3D printing technology, which allows designers to unleash their creativity by adopting the intricate forms inspired by nature. The study illustrates that furniture boasting such complex organic designs can be realized using a variety of 3D printing techniques, including Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Stereolithography (SLA), Laminated Object Manufacturing (LOM), screw-extrusion 3D printing, and cutting-edge robotic 3D printing methods. By embracing these advanced technologies, designers can push the boundaries of traditional furniture aesthetics and functionality, resulting in pieces that are not only visually stunning but also reflect the wonders of nature in their structure and form.

A thorough analysis of structural inspirations derived from natural systems demonstrates that furniture can achieve critical functional attributes—including enhanced structural integrity, flexibility, optimal load distribution, and effective pressure management—by emulating the anatomical configurations of bones, trabecular systems, muscular structures, and tendons. These natural forms exhibit exceptional strength and resilience, suggesting that their replication can significantly enhance the performance and durability of furniture. Additionally, the diverse flora found in nature provides rich inspiration for 3D-printed furniture design, influencing both aesthetics and structural integrity. Drawing from cellular structures and the physical characteristics of various plant species enriches the creative process, leading to innovative, nature-inspired designs.

The concept of biomimicry has historically exerted a significant influence on design, and with the continual advancement of 3D printing technology, we are likely to witness a remarkable proliferation of organic and intricate furniture forms inspired by natural phenomena within interior architectural contexts. This anticipated evolution is set to redefine design paradigms, offering a unique array of creative possibilities that not only enhance aesthetic appeal but also emphasize the potential for cultivating sustainable and adaptive solutions in contemporary furniture design. By integrating biomimetic principles, this approach fosters a deeper symbiotic relationship between human living environments and the natural world, ultimately contributing to a more harmonious coexistence.

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CHAPTER 3

EXAMINATION OF EXHIBITION METHODS OF DIGITAL MUSEUMS

Onur KILIÇ[1]

1 Dr Öğr. Üyesi, Çukurova Üniversitesi, onured4@gmail.com

Abstract

In museums, the main goal is to convey historical or meaningful expressions to the user. Exhibition styles refer to interior elements where the product takes the leading role and becomes a part of the space. Exhibition elements, where the product placed in the space is aimed to be seen by users from different angles, vary depending on the nature of the product. A different effect is needed in the exhibition style of some small-scale objects and in the remains that need to be perceived as a whole on large surfaces like mosaics. It has been deemed necessary to examine the exhibition methods of digital museums, which are beyond the classical exhibition concept. In this context, interior designs of digital museums located in different geographies have been examined. It has been observed that floor, wall and ceiling surfaces are mostly used as screens for exhibition purposes. In addition, it has been observed that light and darkness are used to make the context in the space felt. It has been concluded that museums, which have diversified with virtual museum and digital museum types in recent years, will turn into places where technology is at the forefront with the use of artificial intelligence.

Museum Interior Design

As an important carrier of social and cultural heritage, museums help understand the political, economic, scientific and cultural structures of a country or region, and are also a microcosm of a country or region (Zhou et al., 2022). As people spend more and more time visiting museums, more accurate requirements for the indoor environmental conditions of these limited spaces are needed (Cirrincione et al., 2024). It has been recognized that one of the fundamental issues in the design of museums is the interaction between the layout of the space and the arrangement of objects, and spatial configurations are strongly related to didactic narratives, social implications and curatorial intentions. However, how museums work from a spatial perspective has not yet been extensively studied. Collecting and displaying is a kind of social activity of recontextualizing objects; therefore, museums play a role in arranging, creating or creating a kind of meaningful “whole” (Lee and Kim 2022). There has been a significant change in the morphological characteristics of a museum: collections were usually displayed in either “centrally planned rooms” or “long galleries” until the 17th century, but from the 18th century onwards there was a strong tendency to arrange collections in a spatial order (Lee and Kim 2022;

Pevsner, 1976). Contemporary museum practices must accommodate diverse visitor preferences and generate operational funds beyond public resources by increasing ticket sales through personalized visitor routes. This requirement has led to an increasing tendency to restructure permanent collections through temporary exhibitions to increase performance and revenue (Medaković et al., 2024). The floor plan designs of traditional museum exhibition halls are usually developed according to the location and fluid accessibility of the exhibits. However, there are usually many floors in the same building and multi-story exhibition halls are similar to each other, so architects often spend a lot of time and energy designing the floors separately. Museum exhibition hall floor plan design is an important aspect of architectural environmental design. It not only affects the design of the museum's architectural environmental space and the aesthetic effect of the exhibition hall, but also has a direct impact on the presentation of exhibition content and visitor experience (Min et al., 2023).

Museum Exhibition Formats

Today, the field of museums is experiencing inadequacies in terms of preservation and heritage, as well as problems with individual exhibitions. With the innovations brought by the digital age, innovative exhibition formats and interaction forms in museums can offer visitors new exhibition experiences (Zhang and Liu, 2023). Museums have already adopted new technologies as part of their exhibitions, and many of them include augmented or virtual reality works. Contemporary museums are obliged not only to adapt to the current status quo and follow current trends, but also to shape future cultural experiences (Margetis et al., 2020). Interactive systems are being developed using VR technology, sensors, and gesture recognition to improve visitor engagement. This includes designing systems that appeal to sensory, behavioral, cognitive, and emotional experiences, making museum visits more immersive and educational (Gao, 2024). Virtual reality (VR) is a promising technology for museums, offering visitors the opportunity to offer engaging and interactive interpretations of the past. The recent proliferation of headsets shows that it can be practical and affordable for many museums to use this potential. This raises the question of how museum professionals can integrate VR into their museums in a way that is scalable in terms of visitor flow and adapts to different environments, providing engaging experiences

(Tennent et al., 2020). Display methods are being optimized to enhance the flow experience, which significantly affects visitors' intention to use VR. Familiarity with VR can enhance this effect and indicates the need for user-friendly interfaces (Wang et al., 2023). The cultural heritage sector is increasingly integrating augmented and virtual reality (VR) solutions to meet the display and interpretation needs of their collections. As research in the field increases, the entertainment and learning effects of such applications are also increasing (Tsita et al., 2023). Many museums, archives, libraries, and institutes containing Cultural Heritage (CH) objects are digitizing their collections for research, restoration, and preservation purposes. In parallel, various applications are being integrated for the on-site and remote presentation of digitized artefacts. Augmented Reality (AR) and Virtual Reality (VR) applications are used to attract new audiences with their positive effects on visitors' experiences (Jung et al., 2016; Tsita et al., 2023). In recent years, the use of technology in the museum context has changed radically. It has evolved from displaying information to providing emotional, immersive and rich experiences related to heritage. Virtual interactive media has the potential to reclaim museums as an important place in our increasingly digital society. The emergence of augmented reality glasses offers the opportunity to test and implement new methodologies suitable for this purpose. However, most of the first examples developed in recent years have not benefited from the possibilities of this new medium. Recent museum practices have begun to use online digital resources as a way to improve the technological interfaces between works and viewers. Economic and cultural pressures have made it necessary to rediscover the role and importance of museums and heritage institutions in the search for new and wider audiences, especially for young audiences who have stayed away from museums. Technology has proven to be an important tool in achieving this (Martí-Testón et al., 2023). Figure 1 shows a virtual reality museum experience.

Figure 1. VR Museum Experience
https://thekremercollection.com/museum/

In order to enable more people to visit museums comfortably and comprehensively, the introduction of digital technologies such as virtual reality and augmented reality in museum exhibitions is a need of the times to attract visitors' attention and promote the dissemination and transmission of traditional culture (Han et al., 2022).

Examining Digital Museum Exhibition Formats

Planning experience design in both real and virtual museums is very complex, especially when digital content is juxtaposed with real collections. Researchers, curators, creators and software developers in this field must work together to evolve towards a more efficient connection between visitors, collections and digital applications (Pietroni, 2019). Two years of pandemic and quarantines have accelerated the digital transformation process in many museums. The term digital transformation refers to the transformative condition for museums where digital thinking, applications and tools have gained a normative presence that permeates all levels of their operations and functions (Finnis et al., 2022; Mason, 2022). Today, more and more museums are embracing digitalization, but there is still no real and common awareness of how virtual and real content will interact and how to design the best experience for users. Despite the great contribution that multimedia, virtual reality and mixed reality can make to the museum sector, many curators still seem reluctant to exploit the full potential of these languages, especially in permanent hardware. They usually capture aspects that are more compatible with the traditional didactic approach and remain particularly skeptical of the emotional components of the narrative. In fact, telling a story implies the creation of a possible "reconstruction" of human activities, behaviors, thoughts, values, both in terms of the physical aspect of the cultural heritage and its contexts. A story is a bridge between reality and imagination (Salmon, 2007; Pietroni). Figure 2 shows an example of holographic narration.

Figure 2. Holographic Showcase (Pietroni, 2019)

Hologram technology is seen as an important part of establishing effective communication with users in spaces that have an exhibition function. In museum buildings, hologram technology is sometimes used to revive the historical atmosphere.

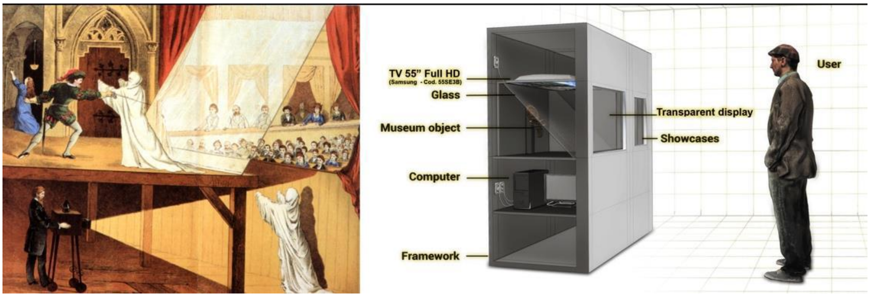

Figure 3. Pepper's Ghost technique (left) and diagram used in theatres in the 19th century. Version created using digital technologies (right) (Pietroni, 2019)

In the world of digital information, visualization of information in public spaces is applied in various formats, such as advertising, useful information, and provision of critical information in cases of accidents, natural disasters, etc. (Pattakos et al., 2023). In the context of a museum visit, providing sufficient information about the artifacts of a social group related to their social and historical context is especially important in places where the objects themselves are not self-explanatory (Booth, 1998; Pattakos et al., 2023). Discovering the challenges that museum professionals must address and the values associated with the "digital" are of critical importance in the context of today's rapid sociocultural and technological changes. Being "behind the scenes" of museums leads to systemic problems in their digital transformation. These systemic problems related to skills and knowledge, human and financial resource deficiencies cause museum professionals to constantly struggle to keep up with the rapid changes in the digital world. Technologies with limited resources are always at risk of obsolescence and abandonment (Nikolaou, 2024). Holography pioneers Gabor, Leith, Upatnieks and Denisyuk predicted very early on that the ultimate 3D display would be based on this technique. This belief was based on the fact that holography was the only approach that could provide all the optical cues interpreted by the human visual system. Holographic 3D displays have been a long-standing dream, facing challenges on all fronts: computation, transmission and presentation (Blanche, 2021).

Figure 4. Interaction with holographic display
https://www.digitalmeetsculture.net/wp-content/uploads/2013/05/chasen

Projection-type holographic three-dimensional display is accelerating its adoption in industrial applications such as digital signage, in-car head-up displays, smart glasses, and head-mounted displays by simultaneously increasing the screen size and visual angle (Wakunami et al., 2016). Augmented reality applications have been found to trigger user interaction and emotional bonds, enhance the learning process, and make museum visits more meaningful (Gong et al., 2022). (Figures 4 and 5)

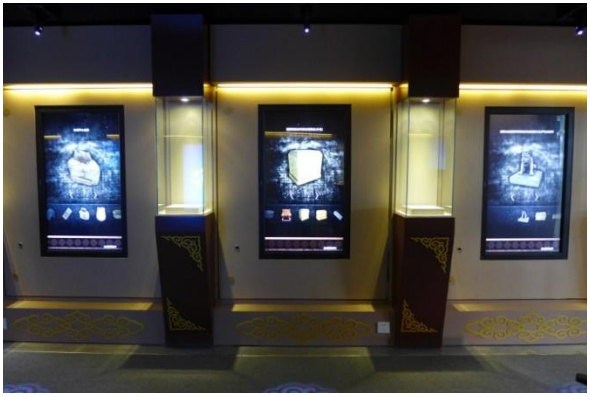

Figure 5. Holographic displays
https://www.digitalmeetsculture.net/wp-content/uploads/2013/05/chasen

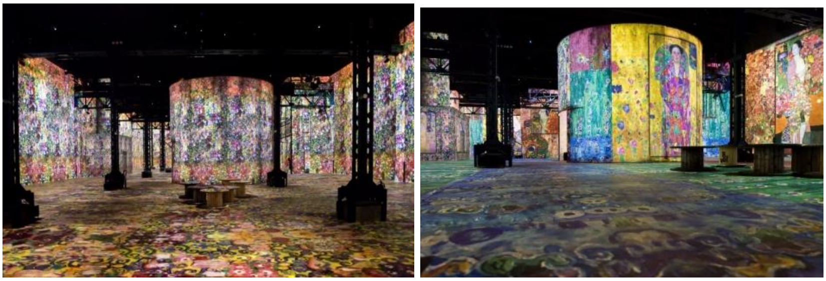

Figure 6. Paris's first digital fine arts museum
https://www.dezeen.com/2018/08/29/atelier-des-lumiere-paris-digital-museum-fine-artdesign/

In digital museums, the display units are all the surfaces surrounding the space. Ceiling, floor and wall surfaces act as a variable screen and are effective in creating the desired atmosphere. Surfaces can interact with users and guide them in terms of the display order.

Figure 7. EPIC Irish Emigration Museum, Dublin Ireland
https://nexttourismgeneration.eu/digital-museums-epic/

Research on VR applications for museum exhibitions mainly focuses on deep gaming experiences and interactive 3D heritage. As a result, visitor engagement and access to cultural content are increasing. The adoption of VR technology has the potential to revolutionize user experiences in the cultural heritage sector, reshaping the overall landscape of museums and exhibitions (Li et al., 2023). Augmented reality (AR) has gained tremendous popularity and acceptance in the last few years. Augmented reality is, in fact, a viable and adaptable solution for many fields. Its development requires a combination of integrated components, different immersive experiences, and solutions. These AR solutions involve tracking the reference point to make virtual objects visible in a real scene. Similarly, imaging technologies merge the virtual and real world with the user's eyes (Syed et al., 2022).

Figure 8. Tokyo Digital Art Museum
https://www.japan.travel/de/de/japanbucketlist/digital-art-museum-tokyo/

Augmented reality (AR) and virtual reality (VR) applications in museums significantly increase user engagement by providing immersive experiences that traditional displays cannot offer. Studies have shown that VR simulations can increase user engagement and have a more positive impact on visitors' emotions compared to non-VR methods. This is evidenced by the increase in positive emotions and the decrease in negative emotions during VR museum tours (Jangra et al., 2025).

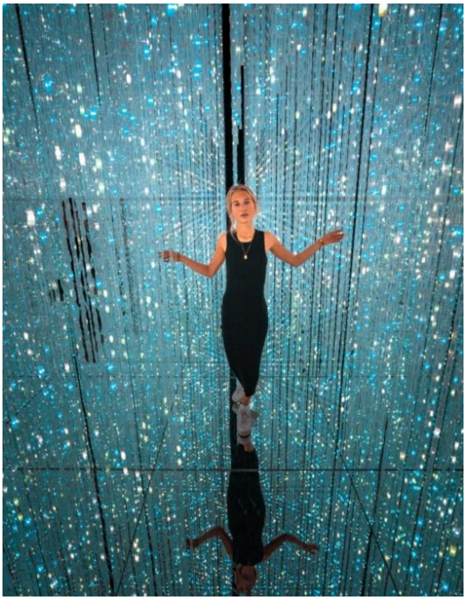

Figure 9. Tokyo Digital Art Museum
https://www.japan.travel/de/de/japanbucketlist/digital-art-museum-tokyo/

Augmented Reality (AR) system is the technology that surrounds digital information such as images, sounds or texts to encompass the user's real-world perception, providing an enriched and interactive experience. It has become a powerful tool to improve human perception and decision-making in various fields, including industrial, automotive, healthcare and urban planning (Mendoza-Ramírez et al., 2023).

Conclusion

Museum structures include volumes where objects of historical importance are exhibited and which must have interior design features. Depending on the feature of the exhibited object, the use of surfaces, pedestals or display elements is preferred. Today, with the development of technological possibilities, the classical museum concept is giving way to digital museums. It is seen that digital museums are designed to make users feel a concept or emotion beyond the exhibition of historical objects. However, the opportunity to examine objects that are not possible in close contact holographically is among the positive features of digital museums. Thus, it becomes possible to have a different experience by interacting with the exhibited object. This experience arouses curiosity in users and makes the space attractive as a whole. It is evaluated that digital approaches will continue to increase in museum interior designs in the future. It is thought that interior designers should consider spaces that have an exhibition function as spaces where the technological possibilities of the future are also exhibited.

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