ISSN 1309-6915

MEGARON

Megaron is indexed in Web of Science, Emerging Sources Citation Index (ESCI), Avery Index to Architectural Periodicals (AIAP), TUBITAK TR Index, EBSCO Host Art & Architecture Complete, Arts Premium Collection, ProQuest, SciTech Premium, ERIH Plus, DOAJ, Gale/Cengage Learning and Ulrich's.

Volume 21
Number 1
Year 2026

YTU PRESS

www.megaronjournal.com

ISSN 1309-6915

MEGARON

Volume 21 Number 1 Year 2026 - March

ISSN 1309-6915

MEGARON

Volume 21 Number 1 Year 2026 - March

ISSN 1309-6915

MEGARON

Volume 21 Number 1 Year 2026 - March

Abstracting and Indexing: Megaron is indexed by Web of Science, Emerging Sources Citation Index (ESCI), Avery Index to Architectural Periodicals (AIAP), as “national peer reviewed journal” in ULAKBIM Social Sciences Databases by TUBITAK-TR Index, EBSCO Host Art & Architecture Complete, Arts Premium Collection, ProQuest, ProQuest Central Essentials, ProQuest One Academic, SciTech Premium, ERIH PLUS, DOAJ, Gale/Cengage Learning, Ulrich’s and IdealOnline.

Journal Description: The journal is supported by Yildiz Technical University officially, and is a blind peer-reviewed free open-access journal, published bimontly (March-June-September-December).

Publisher: Yildiz Technical University

Publisher House: Kare Media

Owner: Sırma Turgut

Managing Director: Sırma Turgut

Editors-In-Chief: Mehmet Doruk Özügül, Tuğçe Şimşekalp Ercan

Co-Editors: Bora Yerliyurt, Neslinur Hızlı Erkılıç

Language of Publication: English

Frequency: 4 Issues

Publication Type: Online e-version

Megaron Logo Design: Tolga Akbulut

Correnspondence Address: Yıldız Teknik Üniversitesi, Mimarlık Fakültesi, Merkez Yerleşim, Beşiktaş, 34349 İstanbul, Türkiye

Tel: +90 (0)212 383 25 85

Fax: +90 (0)212 383 26 50

E-mail: megaron@yildiz.edu.tr

Web: www.megaronjournal.com

Free full-text articles in Turkish and English are available at www.megaronjournal.com.

ISSN 1309-6915

MEGARON

Volume 21 Number 1 Year 2026 - March

CONTENTS

ARTICLES

Megaron, Vol. 21, No. 1, pp. 1–17, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.27448

Article

Text-to-image artificial intelligence in interior architecture design: A multi-criteria decision-making approach

Muhterem Hoser[1], Ayse Gül Gemci[2], Erdem Koymen[2]

[1]*International Balkan University, Faculty of Engineering, Skopje, Northern Macedonia*
[2]*Department of Architecture, İstanbul Sabahattin Zaim University, Faculty of Engineering and Natural Sciences, İstanbul, Türkiye*

ARTICLE INFO

Article history
Received: 12 September 2025
Revised: 20 December 2025
Accepted: 7 January 2026

Key words:
Generative AI; text-to-image AI systems; deep learning; spatial organization; architectural design; multi-criteria decision making; limitations of AI in Design.

ABSTRACT

This study comprehensively evaluates the contributions of text-to-image artificial intelligence (AI) systems to interior architectural design using multi-criteria decision-making (MCDM) methods. Six platforms, DreamStudio, MidJourney, Leonardo AI, Artbreeder, Craiyon and DALL-E, were examined by an expert panel of interior designers and architects and analyzed using MCDM techniques including TOPSIS, AHP, VIKOR, ELECTRE, and PROMETHEE. The analyses revealed DreamStudio's strengths in spatial organization and material harmony, while MidJourney stood out for its ability to generate dynamic, balanced, and visually diverse compositions. Correlation analysis among the MCDM methods enhanced the reliability of the findings, particularly highlighting a strong alignment between TOPSIS and AHP (r=0.997). The study demonstrates the strong aesthetic potential of current AI systems but underscores their limitations in fundamental design elements like spatial logic and cultural relevance. Aesthetic biases and ethical considerations are also addressed. Future research should integrate user experience and designer perspectives to explore a more meaningful and holistic integration of AI into interior design processes.

Cite this article as: Hoser, M., Gemci, A. G., & Koymen E. (2026). Text-to-image artificial intelligence in interior architecture design: A multi-criteria decision-making approach. Megaron, 21(1):1–17.

***Corresponding author**
*E-mail adress: ayse.gemci@izu.edu.tr

INTRODUCTION

Artificial intelligence (AI) is rapidly transforming creative and design-oriented disciplines, fostering new possibilities across architecture, interior design, and other visually driven fields (Boden, 2018; Russell & Norvig, 2016). Interior design stands at the intersection of aesthetics and functionality, making it especially sensitive to innovations that streamline and enrich the design process. AI enables more efficient use of fundamental design elements such as spatial planning, color harmony, material selection, and form (Kalay, 2004), allowing designers to accelerate workflows and generate innovative solutions. With the growing integration of natural language processing (NLP) and deep learning technologies, AI has begun to act not only as a productivity tool but also as a partner in creative ideation. One notable advancement in this context is the emergence of text-to-image AI systems, which convert verbal expressions into visual outputs. These systems, such as MidJourney, DreamStudio, and Leonardo AI, allow designers to explore and materialize design concepts rapidly using natural language prompts (Wang et al., 2023). They enhance creativity and communication in the conceptual phase by providing real-time, high-resolution visualizations of interior spaces.

While the application of text-to-image AI tools has been studied in graphic design, fashion, and product design, their use in interior architectural design remains largely unexplored, particularly with respect to both functional and aesthetic criteria. Existing literature has largely focused on presenting individual tools, with limited research offering systematic, comparative evaluations. Crucially, there is a significant lack of studies that employ rigorous, multi-faceted decision-making frameworks to benchmark these AI systems against the core components (e.g., space, light, material) and fundamental principles (e.g., balance, harmony, hierarchy) that define professional interior architecture practice. This gap makes it difficult for designers to make informed choices about which AI tool is best suited for specific design tasks and conceptual phases. Addressing this gap, the present study aims to analyze the performance of six prominent text-to-image AI systems, DreamStudio, MidJourney, Leonardo AI, Artbreeder, Craiyon and DALL-E, in the context of interior architectural design. The study adopts a multi-criteria decision-making (MCDM) framework to evaluate these systems across key interior design components (e.g., space utilization, lighting, texture, furniture arrangement) and fundamental design principles (e.g., balance, contrast, hierarchy, rhythm) (Artbreeder, 2024; Midjourney, 2022; Blockchain Council, 2024; Craiyon, 2024). It also examines the consistency of different decision-making methods through correlation analysis. By identifying the strengths and limitations of each system, this study contributes to the evolving discourse on AI-assisted design, offering practical and theoretical insights into how these technologies can be integrated into future interior design workflows. In this context, the study seeks to address the following research questions:

- To what extent are current text-to-image AI systems capable of producing effective visuals in alignment with interior architectural design criteria and fundamental design principles?
- When the performances of different AI systems are compared using multi-criteria decision-making (MCDM) methods, which systems stand out, and what factors account for these differences?
- How do text-to-image AI systems contribute to, or fall short in, supporting the creative process within the field of interior architecture?

Research Design and Evaluation Framework

This study employed a structured, multi-phase methodology to evaluate the performance of leading text-to-image artificial intelligence systems in interior architectural design. The research consisted of three primary stages: (1) Scenario-based visual generation using AI prompts; (2) expert-based evaluation of generated visuals using interior design components and fundamental design principles; and (3) comparative performance analysis using multi-criteria decision-making (MCDM) methods.

In the first phase, six widely used text-to-image AI platforms were selected for evaluation: DreamStudio, MidJourney, Leonardo AI, Artbreeder, Craiyon and DALL-E. These systems were chosen based on their accessibility, popularity in design communities, and capabilities to generate photorealistic or stylized interior scenes using natural language prompts. MidJourney and Leonardo AI were used via prompt engineering plugins integrated with ChatGPT, allowing for the generation of detailed and semantically rich prompts in English. These prompts were designed to reflect five distinct interior scenarios, each representing a unique spatial theme such as sustainability, creativity, luxury, playfulness, and rustic aesthetics. ChatGPT was not fine-tuned with custom training data; instead, its general capabilities were utilized through targeted prompt engineering informed by interior design literature. Scenario-based prompts were created using both the Midjourney Prompt Generator (V6) and the Leonardo AI Prompt Maker to generate a diverse and rich initial pool of prompt text. For the final image generation and subsequent expert evaluation, the more detailed and contextually rich prompts from the Leonardo AI generator were consistently used across all five scenarios to ensure comparability.

In the second phase, the generated visuals were evaluated by a panel of professional experts from interior design and architecture disciplines. The evaluation criteria were derived from established design theory (Ching, 2007; Pile, 2007; Hill & Matthews, 2007), and included key interior architecture components (e.g., space utilization, light, color, material, furniture) and design principles (e.g., harmony, balance, contrast, hierarchy, rhythm). Each expert scored the visuals on a 100-point scale across each criterion, and the average of these scores was calculated to represent each system's overall performance per scenario. To ensure a balanced and reliable evaluation process, the expert panel consisted of 30 professionals, 15 architects and 15 interior architects, each with over 10 years of experience in their respective fields. The group was assembled with attention to disciplinary diversity and gender balance to ensure fair and informed assessments of spatial and aesthetic quality in AI-generated designs. The panel comprised practitioners who actively and routinely integrate AI-powered tools into their daily professional practice, providing them with a critical, user-informed perspective essential for evaluating AI-generated design outputs.

In the third phase, five MCDM techniques were applied to synthesize the evaluation data and compare the performance of AI systems from multiple decision perspectives: TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), AHP (Analytic Hierarchy Process), VIKOR (VlseKriterijumska Osteomalacia I Kompromisno Resenje), ELECTRE (Elimination and Choice Expressing Reality), and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation). These five methods were selected for their complementarity in addressing different decision-making perspectives common in design evaluation: TOPSIS ranks alternatives by their geometric distance from an ideal solution, providing a clear performance benchmark (Chakraborty, 2022). AHP decomposes the problem into a hierarchy and uses pairwise comparisons to derive priority weights, effectively capturing expert judgment (Lin et al., 2024). VIKOR focuses on identifying a compromise solution that minimizes individual regret, useful for scenarios with conflicting criteria (Ceballos et al., 2018). ELECTRE employs outranking relations to establish dominance between alternatives, handling non-compensatory decisions effectively (Chakraborty et al., 2023). Finally, PROMETHEE ranks alternatives based on the net flow of preferences between them, offering a nuanced view of relative strengths and weaknesses (Deshmukh, 2013). Applying this suite of methods ensured a robust, multi-faceted evaluation less susceptible to the bias of any single algorithmic approach.

To assess the methodological robustness of the MCDM process, a correlation analysis was conducted comparing the rankings generated by each method. A Spearman rank correlation matrix was constructed to examine the degree of consistency between the decision-making models and to determine whether similar trends emerged across methods. This analysis aimed to validate the reliability of the overall ranking results and reveal how congruent the outcomes were across different algorithmic perspectives. This integrative approach allowed for both a qualitative and quantitative assessment of the AI systems, providing insights not only into which tools performed best under specific design conditions, but also into the methodological coherence of the evaluation framework itself.

Prompt Engineering and ChatGPT Plugins (GPTs)

Prompt engineering is a technique aimed at optimizing user inputs in interactions with artificial intelligence models to obtain the best responses (Liu et al., 2023). It emphasizes the importance of creating inputs in the correct structure to achieve the desired output when interacting with models like GPT-4 and BERT (Brown et al., 2020; Reynolds & McDonell, 2021). This technique maximizes the model's understanding and response capabilities, thereby providing more accurate and creative solutions (Gao et al., 2020; Radford et al., 2019) (Figure 1). GPTs are large-scale language models whose functionality is enhanced through plugins (Brown et al., 2020; Radford et al., 2019). Plugins add capabilities such as real-time data access, translation, and generating output in a specific format.

Figure 1. A basic prompt can consist of a single word, a single expression, or an emoji. In prompt texts, (A) visual URLs affect style and content, (B) the text description determines image quality, and (C) parameters control aspect ratio and model changes (Midjourney, 2024).

Midjourney Prompt Generator (V6): Artificial intelligence-based tools are becoming increasingly important in digital art and design. Platforms like the Midjourney Prompt Generator (V6) optimize visual production by materializing users' creative visions. This model transforms vague requests into aesthetic commands and offers various options. Users elaborate their visual ideas with elements like subject, style, or theme, and the model generates five customized prompts. The visual is created using the selected prompt, and the process is refined with feedback to produce impressive visual content. For example, when a user requests a depiction of a modern and minimalist living room, the model produces a prompt like the following:

Prompt Example: "A photorealistic image of a modern, minimalist living room featuring an open floor plan, large floor-to-ceiling windows, a neutral color palette, sleek furniture, and elegant textures. Natural lighting enhances the simplicity of the space. Created using high-resolution photography, minimalist design, clean lines, modern furniture, soft textures, emphasis on natural light --ar 16:9 --v 6.0"

When this prompt is used in Midjourney V6 to generate an image, it provides the user with an output that includes the desired aesthetics and details.

Leonardo AI Prompt Generator (Leonardo AI Prompt Maker): The Leonardo AI Prompt Generator is a ChatGPT-based plugin for text-to-image artificial intelligence systems. It prepares prompts that include details like the image's subject, style, type, and camera angle, producing various visuals. While it operates in English, it can detect Turkish inputs and automatically create English prompts. Supporting creative potential in digital art and design projects with its user-friendly interface, it is quite simple to use: The user specifies the features of the visual, the system generates four prompts, and the desired visual is created with the selected prompt.

Prompt Example: "Create a photorealistic image of a living room designed to meet interior design standards. The room has a modern and minimalist style with neutral colors and natural light. It includes a large, comfortable gray sofa, a glass coffee table, and a cream-colored textured rug. Large windows offer a view of the tranquil garden outside. The space is accented with subtle artworks and indoor plants. Lighting should be soft and natural to highlight the clean lines and open space. Use a wide-angle lens effect to capture the entire room."

When this prompt is entered into Leonardo AI, visuals with the desired features are produced. These two plugin systems can also be used in other text-to-image AI applications, allowing users to generate visuals with similar prompts on different platforms. The Leonardo AI Prompt Generator makes it easy for users to prepare detailed and customized prompts in text-to-image AI systems, enabling them to produce the visuals they want. This ChatGPT-based plugin offers a practical and functional solution for users by detecting Turkish inputs and creating English prompts.

Components and Basic Design Principles of Interior Architecture

Interior architecture is a scientific art that improves people's interactions with spaces by balancing aesthetics and functionality. Its fundamental components are space, light, color, material, texture, and furniture, and these elements determine the atmosphere of the space and the user experience. Interior architecture not only enhances visual appeal but also optimizes users' interactions with space (Ching, 2007).

Components of Interior Architecture: Interior architecture prioritizes the user experience by addressing factors such as space planning, lighting, color and material selection, furniture, and accessories. Good space planning ensures efficient use and flow of areas, while lighting directly affects the atmosphere of space (Hill & Matthews, 2007). Color and material choices determine the aesthetics of the space, while furniture selection defines functionality and comfort.

- **Space Utilization:** Space lies at the core of interior architecture. It directly influences how users move within and experience space. Balancing functionality and aesthetics is critical for successful space design. The psychological and emotional needs of users should also be considered in space planning (Ching, 2007; Königk, 2011).
- **Light:** Light has a significant impact on the perception and atmosphere of space. Natural and artificial light sources shape the functionality and aesthetics of the environment. Proper lighting improves the mood of space while also enhancing energy efficiency (Heerwagen & Leah Zagreus, 2005).
- **Color:** Colors directly affect the atmosphere of the space and the mood of the users. Color selection should align with the purpose of the space and support its aesthetic value. Color contrast and harmony enhance the visual appeal and influence the emotional responses of users (Albers, 1963).
- **Material and Texture:** Materials and textures determine the aesthetic and functional characteristics of space. Natural materials evoke feelings of warmth and naturalness, while modern materials offer a contemporary look. Textures enrich the user experience by adding depth and character to space (Ashihara, 1986).
- **Form:** Form defines the physical structure and visual perception of space. Geometric and organic forms shape the atmosphere and aesthetic qualities. The interaction of form with material, texture, and color strengthens the overall aesthetics of space (Ching, 2007).
- **Void:** Void defines the physical boundaries of the space and affects visual perception. Closed and open areas

serve different functions in terms of social interaction and spatial flexibility. Effective use of void increases the sense of openness and usage efficiency in space (Wright, 1975).

- **Furnishings:** Furnishings directly impact the functionality and aesthetics of the space. Elements like lighting fixtures, door handles, and furniture reflect the character and intended use of the space. Properly selected furnishings should align with the overall design concept (Pile, 2007).
- **Sustainability:** Sustainability in interior design aims to reduce environmental impact and increase energy efficiency. Materials obtained from renewable sources and energy-efficient lighting solutions play a significant role in sustainable space design (Kibert, 2016).
- **Design Principles:** Architecture and interior design rely on specific design principles to ensure aesthetics and functionality. These principles determine the perception, use, and interaction within space. Basic design elements include visual components like point, line, form, and color, as well as principles like repetition, balance, contrast, hierarchy, and proportion. These principles help achieve aesthetic and functional goals in the design process (Balaban Varol & Varol, 2023; Lupton & Phillips, 2008).

While these components define the fundamental physical and sensory dimensions of interior architectural space, their effective integration and spatial coherence are achieved through the application of basic design principles, which structure how these elements are perceived, organized, and experienced within the interior environment.

Basic Design Principles in Interior Architecture:
Balancing functionality and aesthetics are crucial in interior space design. Spatial unity refers to the harmonious functioning of different parts of space. Designers guide the perception and usage of space according to principles like harmony, balance, contrast, and hierarchy (Spence, 2020).

- **Harmony and Unity:** Harmony provides visual comfort through the cohesive use of elements like color, texture, and form. Unity is achieved when various parts of space come together around a consistent theme or idea. These principles ensure that users perceive the space as a single composition (Ching, 2007; Pallasmaa, 2024).
- **Balance:** Balance is divided into symmetrical and asymmetrical types. Symmetrical balance consists of equal elements mirrored around a central axis, giving an impression of order. Asymmetrical balance is created by placing elements of different sizes in a balanced manner, providing a more dynamic composition (Çeken et al., 2018).
- **Contrast and Emphasis:** Contrast provides visual diversity by creating opposition among elements like color, texture, and form. Emphasis is used to highlight a specific part of the design. These strategies tell the story of space and direct the user's attention (Shi & Sun, 2019).
- **Hierarchy:** Hierarchy arranges design elements according to their visual importance. It determines the flow of the space and the orientation of users within it. An effective hierarchy makes the space more organized and accessible (Samara, 2008).
- **Proportion and Scale:** Proportion and scale establish the dimensional relationships between elements in the space. Correct use of proportion and scale can make the space feel more expansive, spacious, intimate, or cozy (Ching, 2007).
- **Repetition and Rhythm:** Rhythm is created by the regular repetition of specific forms, colors, and textures. Repetition and rhythm provide visual flow and enhance consistency in space (Rodop, 2017).
- **Movement:** Movement creates a sense of dynamism and flow within space. Transitions between lines and colors offer a visual journey and add energy to the composition (Itten & Van Haagen, 1973).
- **Space and Void:** Space and void determine the aesthetics and functionality of the environment. Empty spaces make the area feel comfortable and open, while filled spaces establish functional arrangement. Proper use of void ensures space is perceived as spacious and balanced (Arnheim, 1954).

These fundamental design principles provide the conceptual and analytical basis for evaluating the quality of AI-generated interior visuals; accordingly, the following section applies these principles as structured evaluation criteria to assess the performance of text-to-image systems in producing coherent, functional, and aesthetically grounded interior architectural representations.

Evaluation of Text-to-Image Systems
In this section, the components of interior architecture and basic design principles discussed in previous studies are evaluated alongside ChatGPT prompts and text-to-image systems. ChatGPT taught interior design criteria and design principles, and based on this information, five draft texts were created to visualize specific interior spaces.

Artificial Intelligence Data Feeding Stage: The most critical stage for the effective functioning of artificial intelligence is data feeding. In this phase, processes such as data collection, cleaning, and labeling ensure that AI algorithms are trained correctly. ChatGPT created visual drafts suitable for the given scenarios by learning interior design criteria (Figure 2).

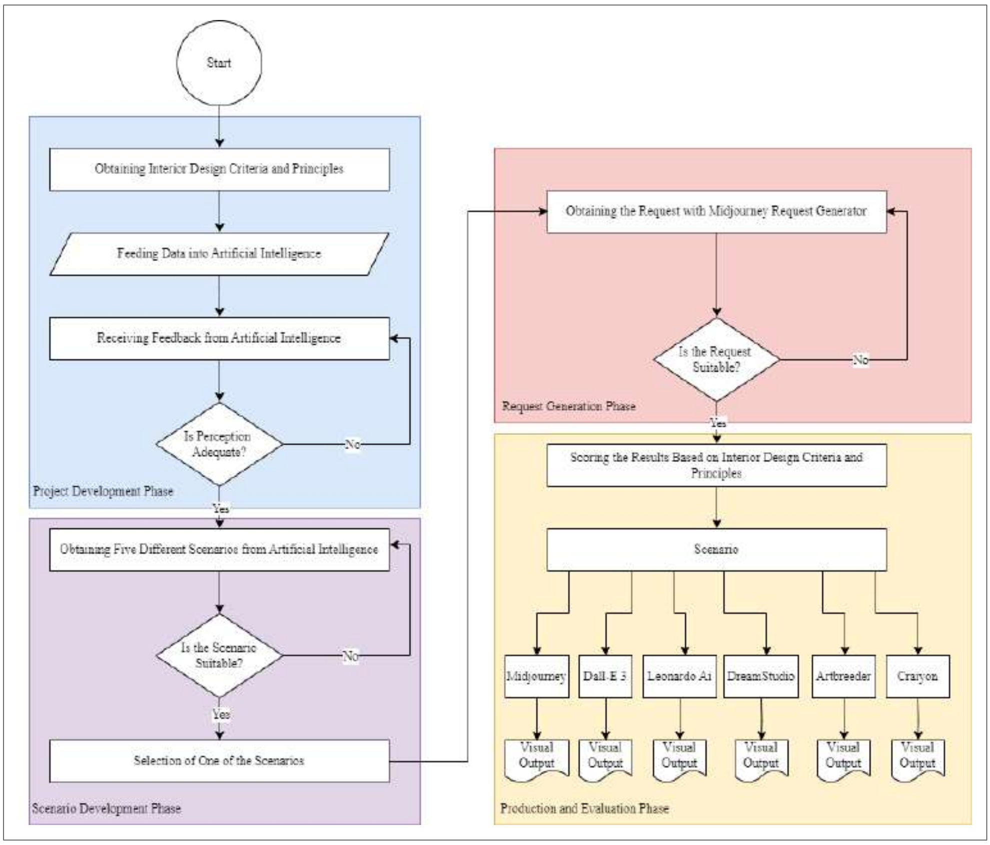

Figure 2. Flowchart of the process (Design by the Authors).

As a result of the evaluation between two different text generators, the Midjourney Prompt Generator was selected, and the drafts created were transferred to this platform. Various prompts were generated via Midjourney, and the desired visual content was produced (Midjourney, 2024) (Figure 3).

Draft Scenario Reviews: Some visuals provided by text-to-image artificial intelligence were excluded from the review because they offered limited views. It was anticipated that visuals showing the full spatial setup are needed to comprehensively compare all criteria.

Draft Scenario 1: A modern living room designed according to sustainability principles. The furniture is made from recycled materials, and natural light is utilized to the maximum extent. The walls are covered with thermal insulation materials with high energy efficiency, and natural landscapes are showcased through large windows. The color palette consists of light pastel tones, creating a spacious and peaceful atmosphere. After applying the procedures described above to this draft scenario, **Prompt 1** emerges.

Prompt 1: A modern living room designed with sustainability principles. Furniture made from recycled materials, walls covered with high energy-efficient insulation materials, large windows showcasing natural scenery. The color palette is composed of soft pastel tones that create a calming atmosphere. Created using photorealistic, natural lighting, soft textures, a tranquil mood, wide-angle view, HD quality, natural appearance --ar 16:9 --v 6.0

The visuals produced with this prompt were evaluated by expert architects and interior designers according to interior architectural design criteria. In the table containing separate columns for each criterion, the compliance percentage of each visual with the criteria was examined in detail. The survey results were formed with the participation of seven architects and seven interior designers, and each component was scored out of 100 (Table 1). Midjourney, DALL-E 3, and DreamStudio AI systems have demonstrated impressive performances by generally receiving high scores in various design principles within interior design and architectural projects. These systems particularly stand out in space utilization, use of light, and color usage. DreamStudio has attracted attention with high marks in space and light utilization, achieving good results especially in criteria such as harmony and unity, balance, and hierarchy. On the other hand, Artbreeder, showing below-average scores, indicates a need for improvement in some areas while receiving more positive evaluations in material and texture. Artbreeder and Craiyon emerge as systems that need development due to their low performance in applying design principles. These evaluations help determine which AI tool might be more suitable for specific design needs and provide important

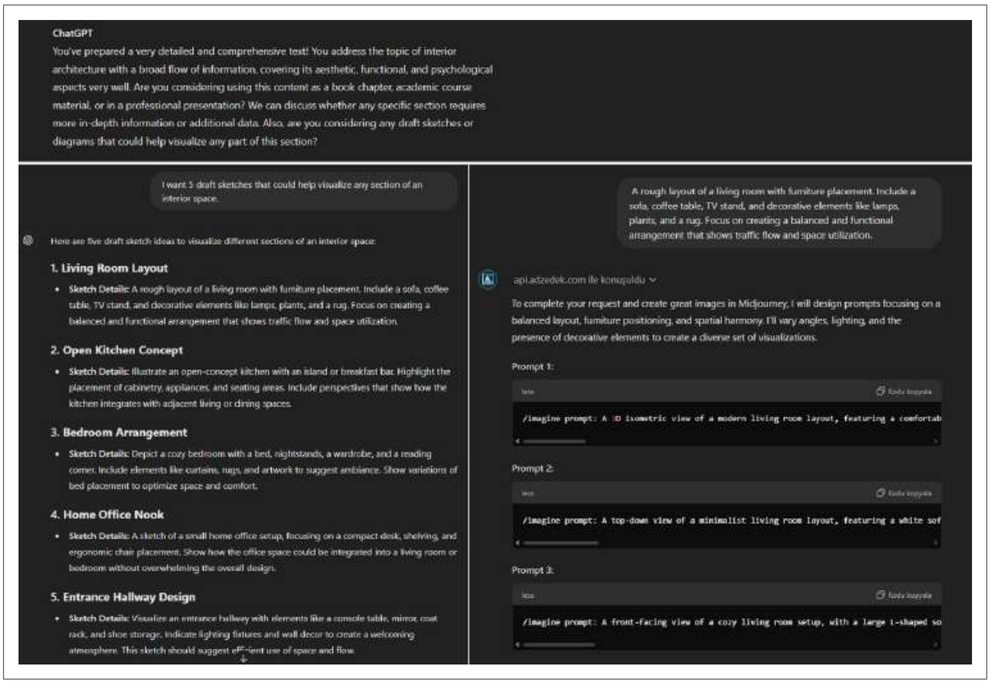

Figure 3. The interfaces of ChatGPT and Midjourney display the appearances of interior architectural components, basic design principles, sample scenarios, and the visual outputs of prompts (OpenAI, 2024).

insights on how these systems can be optimized in design processes (Table 1).

Draft Scenario 2: A workspace is designed with dynamic elements to promote creativity and productivity. The walls are painted vibrant colors and are adorned with artworks containing motivational quotes at certain points. The furniture is ergonomic and modern, including a large desk and a comfortable office chair. The room's layout can be adjusted to offer flexible use for both individual work and small group meetings. After applying the procedures described above to this draft scenario, Prompt 2 emerges.

Prompt 2: A workspace designed with dynamic elements to promote creativity and productivity. Walls painted in vibrant colors, decorated with motivational artwork, ergonomic modern furniture including a large work desk and a comfortable chair. The room layout is adjustable for individual work and small group meetings. Created using photorealistic, vivid style, motivational quotes, vibrant lighting, creative atmosphere, wide-angle view, HD quality, natural appearance --ar 16:9 --v 6.0.

Midjourney, Leonardo AI, and DreamStudio artificial intelligence systems have demonstrated high performance in various design criteria in interior design and architectural projects. Particularly, Midjourney and Leonardo AI have achieved noteworthy results in areas like space utilization, lighting, and color usage. Leonardo AI has also stood out by receiving high scores from interior designers and architects. DreamStudio has generally shown good performance, receiving high marks especially in material and texture usage and form. Conversely, although DALL-E 3 has shown above-average performance in some areas, it has generally received lower scores. Artbreeder and Craiyon have performed poorly in most criteria, falling short in applying design principles. These results help determine which AI tool might be suitable for specific design needs and provide important insights into how these systems can be optimized in design processes (Table 2).

Draft Scenario 3: The bathroom has been redesigned in a luxurious and modern style. Marble countertops and stylish fixtures provide a rich touch. High-gloss ceramic tiles that are water-resistant have been used on the walls. Lighting has been carefully selected to create both functional and atmospheric effects, and the sense of spaciousness has been enhanced with floor-to-ceiling mirrors.

Prompt 3: A bathroom redesigned in a luxurious and modern style. Marble countertops, stylish accessories, glossy ceramic tiles on the walls, carefully selected lighting for functional and atmospheric effects, and floor-to-ceiling mirrors that enhance the sense of space. Created using photorealistic, high-quality lighting, elegant textures, glossy surfaces, wide-angle view, HD quality, natural appearance --ar 16:9 --v 6.0

Midjourney, Leonardo AI, DreamStudio, DALL-E 3, Artbreeder, and Craiyon have been evaluated according to various design criteria in interior design and architectural projects. Leonardo AI and DreamStudio have shown high performance in most areas, while Midjourney has achieved

Megaron, Vol. 21, No. 1, pp. 1–17, March 2026

Table 1. (Draft Scenario 1) Evaluation of text-to-image artificial intelligence systems according to interior architecture components and basic design principles (%)

																			
		MIDJOURNEY			**DALL-E 3**			**LEONARDO AI**			**DREAMSTUDIO**			**ARTBREEDER**			**CRAIYON**		
	Job	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**
Interior Architecture Components	Space Utilization	74	81	78	69	59	64	61	54	58	80	81	81	46	56	51	27	60	44
	Light	77	76	77	70	69	70	41	56	49	73	81	77	63	69	66	40	57	49
	Color	76	80	78	59	63	61	57	63	60	74	71	73	57	54	56	33	50	42
	Material and Texture	63	81	72	61	63	62	57	69	63	69	74	72	59	67	63	24	46	35
	Form	70	83	77	66	67	67	63	66	65	69	80	75	44	57	51	21	50	36
	Void	63	67	65	59	51	55	60	63	62	69	74	72	47	49	48	24	50	37
	Furnishings	57	73	65	53	54	54	63	63	63	76	80	78	39	47	43	17	39	28
	Sustainability	59	74	67	49	56	53	47	63	55	56	70	63	37	41	39	17	46	32
Basic Design Principles	Harmony and Unity	74	80	77	60	57	59	60	63	62	74	80	77	37	50	44	24	51	38
	Balance	70	76	73	61	61	61	57	70	64	73	80	77	36	53	45	21	50	36
	Contrast and Emphasis	50	71	61	47	59	53	54	60	57	66	66	66	47	59	53	30	51	41
	Hierarchy	57	76	67	63	59	61	60	63	62	71	76	74	39	54	47	23	59	41
	Proportion and Scale	66	86	76	66	76	71	66	73	70	81	83	82	51	64	58	24	57	41
	Repetition and Rhythm	53	74	64	67	69	68	57	63	60	71	74	73	46	47	47	23	50	37
	Movement	54	71	63	60	66	63	60	64	62	71	70	71	34	54	44	26	53	40
	Space and Void	64	77	71	63	67	65	64	67	66	71	76	74	41	49	45	26	54	40

good results particularly in space utilization, lighting, and material usage. On the other hand, DALL-E 3 has exhibited above-average performance but received low scores in some areas. Artbreeder and Craiyon have generally shown low performances, indicating that they need improvement. These evaluations reveal how each AI system can adapt to specific design needs and highlight their strengths and weaknesses. This information can be an important guide when deciding which tools to use in design processes (Table 3).

Draft Scenario 4: The playroom is designed to encourage children's creativity and learning abilities. The walls are decorated with interactive and educational murals. The floor is covered with soft and washable rugs. The furniture is sized appropriately for children and has rounded corners to ensure safety against bumps and falls.

Prompt 4: A playroom designed to enhance children's creativity and learning abilities. Walls adorned with interactive and educational murals, soft washable rugs on the floor, and furniture suitable for children's sizes with rounded edges for safety. Created using photorealistic, vibrant colors, fun atmosphere, HD quality, wide-angle view, natural lighting, child-friendly design --ar 16:9 --v 6.0

Midjourney, Leonardo AI, and DreamStudio artificial intelligence systems have drawn attention by receiving high scores across various criteria in interior design and architectural projects. Particularly, Leonardo AI has stood out with very high scores in space utilization, lighting, and color usage. DreamStudio similarly demonstrated good performances but lagged Leonardo AI in some areas. Midjourney generally performed well, notably receiving high scores in lighting usage. On the

Table 2. (Draft Scenario 2) Evaluation of text-to-image artificial intelligence systems according to interior architecture components and basic design principles (%)

																			
		MIDJOURNEY			DALL-E 3			LEONARDO AI			DREAMSTUDIO			ARTBREEDER			CRAIYON		
	Job	Interior Architect	Architect	Average	Interior Architect	Architect	Average	Interior Architect	Architect	Average	Interior Architect	Architect	Average	Interior Architect	Architect	Average	Interior Architect	Architect	Average
Interior Architecture Components	Space Utilization	57	84	71	56	77	67	83	81	82	69	79	74	34	61	48	26	51	39
	Light	69	77	73	44	63	54	80	71	76	77	83	80	33	47	40	23	49	36
	Color	90	83	87	47	70	59	71	77	74	80	86	83	50	59	55	43	49	46
	Material and Texture	66	80	73	49	71	60	69	80	75	54	79	67	37	47	42	21	40	31
	Form	67	84	76	46	71	59	76	84	80	73	81	77	30	40	35	26	41	34
	Void	53	76	65	46	73	60	71	83	77	64	80	72	21	43	32	25	39	32
	Furnishings	63	79	71	51	70	61	74	74	74	59	73	66	29	44	37	26	40	33
	Sustainability	51	66	59	31	54	43	51	54	53	54	61	58	27	34	31	17	30	24
Basic Design Principles	Harmony and Unity	59	81	70	43	74	59	70	74	72	71	74	73	33	44	39	29	36	33
	Balance	59	74	67	47	73	60	61	73	67	67	70	69	27	43	35	20	40	30
	Contrast and Emphasis	69	83	76	56	76	66	81	80	81	66	8	37	47	49	48	34	40	37
	Hierarchy	64	73	69	51	76	64	69	74	72	70	79	75	34	46	40	27	47	37
	Proportion and Scale	67	79	73	63	74	69	80	76	78	73	73	73	47	50	49	33	44	39
	Repetition and Rhythm	66	74	70	56	73	65	76	76	76	67	74	71	41	53	47	34	40	37
	Movement	71	83	77	54	69	62	71	80	76	61	77	69	30	49	40	30	40	35
	Space and Void	54	74	64	56	70	63	76	80	78	69	73	71	26	50	38	26	46	36

other hand, DALL-E 3 received above-average scores in some criteria but showed lower performance in others, presenting an overall mixed picture. Artbreeder and Craiyon exhibited generally low performances, indicating a need for improvement in applying design principles (Table 4).

Draft Scenario 5: The kitchen has an industrial and rustic style. Countertops are made of raw concrete and metal components, and the cabinets are designed from recycled wood. Open shelves are filled with copper pots and pans. Lighting is provided by large metal pendant lamps and wall sconces. The floor is covered with a mixture of natural stone and metal, adding a rustic touch to the space.

Prompt 5: An industrial and rustic-style kitchen. Countertops made from raw concrete and metal components, cabinets made from recycled wood, open shelves filled with copper pots and pans, lighting provided by large metal pendant lamps and wall sconces. Flooring covered with a mixture of natural stone and metal for a rustic touch. Created using photorealistic, industrial design, rustic elements, HD quality, wide-angle view, natural lighting, warm tones, vintage style --ar 16:9 --v 6.0

Midjourney, Leonardo AI, and DreamStudio generally exhibit high performance in design criteria within interior design and architectural projects. Midjourney particularly stands out in space utilization and balance, while Leonardo AI offers superior results in material, texture, and aesthetic harmony. DreamStudio is successful in spatial arrangement and use of void. DALL-E 3 and Craiyon provide above-average results in some areas but have shown lower perfor-

Table 3. (Draft Scenario 3) Evaluation of text-to-image artificial intelligence systems according to interior architecture components and basic design principles (%)

																			
		MIDJOURNEY			**DALL-E 3**			**LEONARDO AI**			**DREAMSTUDIO**			**ARTBREEDER**			**CRAIYON**		
	Job	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**
Interior Architecture Components	Space Utilization	69	77	73	79	79	79	79	81	80	83	74	79	54	70	62	37	49	43
	Light	64	77	71	76	79	78	79	83	81	87	74	81	66	64	65	54	47	51
	Color	60	74	67	74	86	80	80	86	83	86	77	82	44	54	49	43	46	45
	Material and Texture	74	76	75	76	81	79	77	84	81	81	71	76	57	66	62	33	43	38
	Form	74	81	78	71	81	76	76	72	74	77	81	79	50	67	59	31	46	39
	Void	50	74	62	69	76	73	64	73	69	66	67	67	51	54	53	43	40	42
	Furnishings	66	81	74	61	74	68	71	76	74	70	76	73	53	59	56	37	39	38
	Sustainability	50	59	55	49	57	53	56	52	54	63	61	62	37	44	41	24	43	34
Basic Design Principles	Harmony and Unity	73	79	76	74	73	74	84	81	83	83	77	80	54	60	57	34	40	37
	Balance	64	77	71	64	80	72	76	74	75	79	76	78	53	64	59	34	40	37
	Contrast and Emphasis	61	76	69	63	74	69	73	73	73	79	79	79	43	60	52	36	50	43
	Hierarchy	76	80	78	66	73	70	74	80	77	79	80	80	57	67	62	31	41	36
	Proportion and Scale	80	74	77	71	76	74	80	86	83	76	80	78	59	70	65	29	41	35
	Repetition and Rhythm	71	83	77	70	76	73	79	84	82	69	74	72	56	64	60	30	49	40
	Movement	70	81	76	69	74	72	74	81	78	70	79	75	51	67	59	36	46	41
	Space and Void	60	79	70	72	77	75	64	80	72	59	69	64	53	64	59	41	46	44

mance in certain criteria. Artbreeder generally displayed weak performance, being found less successful compared to other systems. Overall, Midjourney and Leonardo AI are the systems demonstrating the highest performance (Table 5).

EVALUATION

To evaluate the overall performance of the selected text-to-image AI systems in interior design applications, five widely recognized multi-criteria decision-making (MCDM) methods were applied: TOPSIS, AHP, VIKOR, ELECTRE, and PROMETHEE (Figure 4). Each method enabled the identification of strengths and weaknesses of the systems from different analytical perspectives, and the results were integrated to support a robust comparative evaluation.

The analysis based on the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, which ranks alternatives according to their proximity to the ideal solution (Chakraborty, 2022), revealed that DreamStudio (*0.78*) and MidJourney (*0.75*) performed closest to the ideal solution. Similarly, the AHP (Analytic Hierarchy Process) method, which utilizes pairwise comparisons in a hierarchical structure (Lin et al., 2008), indicated DreamStudio (*0.85*) and MidJourney (*0.82*) as the most favorable alternatives. These two methods produced highly consistent results, with a strong positive correlation ($r=0.997$, $p=0.00023$), as shown in the correlation matrix analysis.

According to VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), which emphasizes compromise solutions under conflicting criteria (Ceballos et al., 2018),

Table 4. (Draft Scenario 4) Evaluation of text-to-image artificial intelligence systems according to interior architecture components and basic design principles

																			
		MIDJOURNEY			**DALL-E 3**			**LEONARDO AI**			**DREAMSTUDIO**			**ARTBREEDER**			**CRAIYON**		
	Job	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**
Interior Architecture Components	Space Utilization	73	77	75	91	87	89	56	71	64	41	64	53	37	50	44	31	54	43
	Light	76	73	75	90	89	90	47	71	59	53	64	59	37	47	42	43	56	50
	Color	84	86	85	90	84	87	60	76	68	54	66	60	53	57	55	41	56	49
	Material and Texture	77	77	77	89	84	87	57	77	67	34	56	45	36	43	40	37	51	44
	Form	76	81	79	89	80	85	57	74	66	40	60	50	34	50	42	33	50	42
	Void	66	79	73	77	84	81	56	67	62	36	54	45	46	51	49	31	53	42
	Furnishings	71	74	73	87	83	85	54	70	62	33	56	45	33	53	43	31	47	39
	Sustainability	64	60	62	73	73	73	40	64	52	24	44	34	24	46	35	27	47	37
Basic Design Principles	Harmony and Unity	74	77	76	87	81	84	51	69	60	39	54	47	36	47	42	29	44	37
	Balance	69	79	74	89	81	85	56	69	63	31	51	41	30	47	39	27	49	38
	Contrast and Emphasis	74	80	77	83	83	83	51	76	64	37	54	46	34	49	42	36	51	44
	Hierarchy	71	80	76	86	83	85	59	67	63	36	54	45	39	44	42	31	47	39
	Proportion and Scale	73	79	76	86	81	84	51	70	61	39	54	47	41	53	47	39	50	45
	Repetition and Rhythm	73	79	76	86	84	85	56	71	64	40	53	47	40	46	43	33	46	40
	Movement	67	83	75	81	83	82	59	67	63	39	56	48	37	44	41	37	50	44
	Space and Void	63	80	72	74	84	79	51	66	59	34	51	43	37	47	42	37	50	44

DreamStudio was found to be the most balanced choice with a Q value of 0.12. ELECTRE (Elimination and Choice Expressing Reality), which compares alternatives through dominance relations (Chakraborty, et al., 2023), also confirmed the superiority of DreamStudio (*dominance score=3*) and MidJourney (*dominance score=2*).

A significant positive correlation (*r=0.989, p=0.00146*) was observed between ELECTRE dominance scores and overall system performance. PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) results, which ranks alternatives according to their positive and negative flows (Deshmukh, 2013), were consistent with previous findings, showing DreamStudio as the top performer based on its net flow value (*0.42*). However, the PROMETHEE and VIKOR methods presented an inverse relationship, with a strong negative correlation (*r=−1.000, p=1.4e−24*), suggesting divergent evaluative tendencies. These variances highlight how different MCDM methods can prioritize distinct aspects of system performance.

To examine the consistency among the five MCDM approaches, a Spearman rank correlation analysis was conducted (Sedgwick, 2014). The results are presented in Figure 5 which show that while TOPSIS, AHP, and ELECTRE tend to align closely, VIKOR and PROMETHEE exhibit opposing trends in ranking outcomes. This analysis contributes to the methodological transparency of the study and provides insight into how the choice of decision-making method may affect evaluation results.

Table 5. (Draft Scenario 5) Evaluation of text-to-image artificial intelligence systems according to interior architecture components and basic design principles (%)

																			
		MIDJOURNEY			**DALL-E 3**			**LEONARDO AI**			**DREAMSTUDIO**			**ARTBREEDER**			**CRAIYON**		
	Job	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**	**Interior Architect**	**Architect**	**Average**
Interior Architecture Components	Space Utilization	80	80	80	79	80	80	81	77	79	76	67	72	77	56	67	73	73	73
	Light	74	71	73	80	74	77	56	59	58	66	63	65	60	50	55	73	70	72
	Color	71	69	70	76	73	75	64	64	64	70	61	66	66	57	62	69	69	69
	Material and Texture	76	70	73	81	73	77	70	71	71	64	59	62	74	61	68	60	59	60
	Form	79	79	79	83	80	82	73	76	75	70	66	68	74	54	64	69	64	67
	Void	64	80	72	71	77	74	63	71	67	69	61	65	66	56	61	54	66	60
	Furnishings	71	74	73	81	79	80	67	79	73	66	64	65	69	54	62	70	64	67
	Sustainability	64	57	61	66	60	63	56	60	58	57	59	58	56	49	53	59	60	60
Basic Design Principles	Harmony and Unity	81	79	80	83	74	79	77	71	74	69	64	67	71	63	67	59	59	59
	Balance	77	79	78	79	76	78	73	71	72	69	64	67	73	59	66	59	66	63
	Contrast and Emphasis	79	76	78	77	71	74	70	69	70	64	60	62	69	60	65	67	64	66
	Hierarchy	81	79	80	79	76	78	76	64	70	71	56	64	70	61	66	64	67	66
	Proportion and Scale	79	74	77	83	77	80	76	71	74	67	74	71	69	69	69	69	66	68
	Repetition and Rhythm	83	73	78	81	77	79	77	70	74	69	69	69	71	66	69	59	63	61
	Movement	77	73	75	80	76	78	76	64	70	70	67	69	70	64	67	63	66	65
	Space and Void	67	74	71	73	70	72	77	66	72	67	67	67	67	60	64	53	61	57

Figures 6 and 7 synthesize the comparative performance of the evaluated text-to-image AI systems. Figure 6 presents the system rankings derived from individual MCDM methods, while Figure 7 illustrates the aggregated success scores obtained through the integration of all evaluation techniques. Together, these visualizations offer a consolidated assessment of system performance and facilitate the identification of AI tools that are more suitable for specific interior design requirements. The results indicate that DreamStudio and MidJourney consistently outperform the other systems across the majority of evaluation methods, particularly with respect to material–texture coherence, compositional balance, spatial organization, and lighting quality—criteria that are critical to interior architectural design. In contrast, Artbreeder and Craiyon exhibit comparatively lower performance, highlighting their limitations in addressing complex spatial and material relationships. Overall, these findings delineate the current capabilities and constraints of text-to-image AI tools and provide a grounded analytical basis for their more informed and selective integration into future interior design workflows.

DISCUSSION

This study provides one of the first systematic, multi-criteria evaluations of text-to-image AI systems within the specific domain of interior architecture. The consistent outperformance of DreamStudio (Stable Diffusion) and MidJourney across multiple MCDM methods confirms that not all generative AI platforms are equally adept at meet-

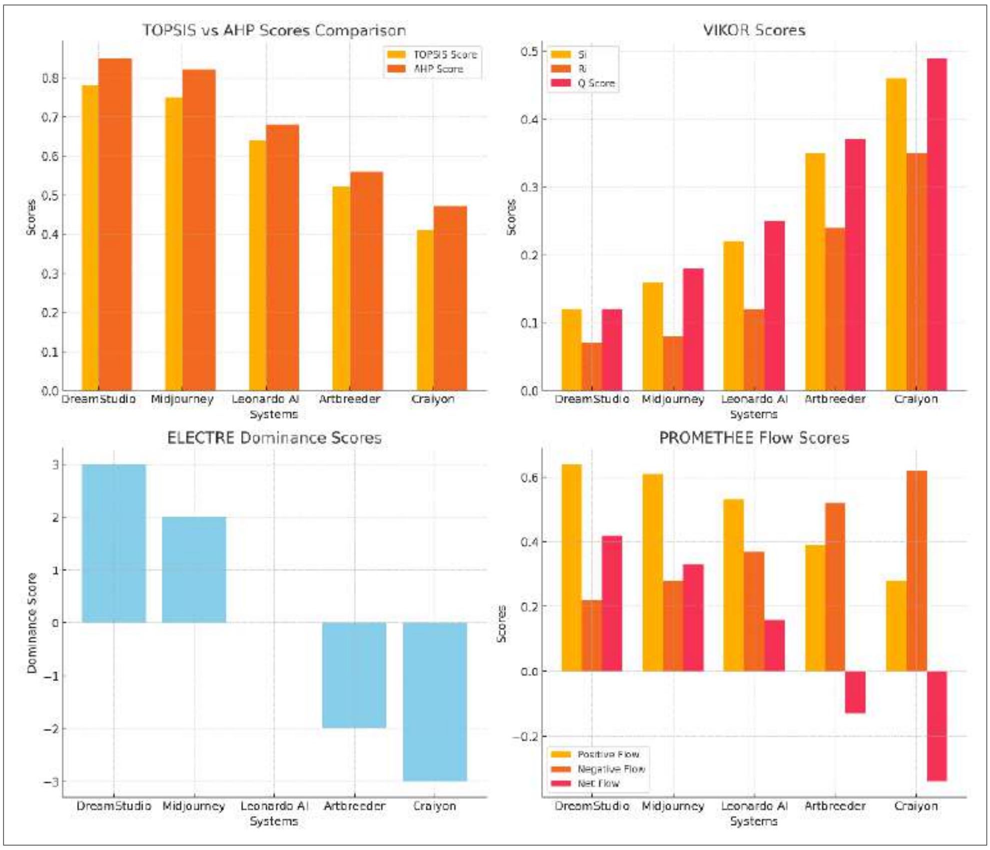

Figure 4. TOPSIS vs AHP Scores, VIKOR Scores, ELECTRE Dominance Scores, and PROMETHEE Flow Scores.

ing the nuanced demands of spatial design. DreamStudio's strength in spatial organization and material-texture coherence can be attributed to its open-source, Latent Diffusion Model (LDM) architecture, which allows for fine-grained control and predictable, high-fidelity output—a key advantage for technical design phases (Rombach et al., 2022). In contrast, MidJourney's proficiency in generating dynamic, balanced, and visually diverse compositions stems from its proprietary model, which is explicitly optimized for artistic expression and creative exploration, making it ideal for initial concept ideation and mood-setting (Holmes, 2023; Oppenlaender, 2023).

The strong alignment between TOPSIS, AHP, and ELECTRE rankings (r>0.989) underscores the methodological

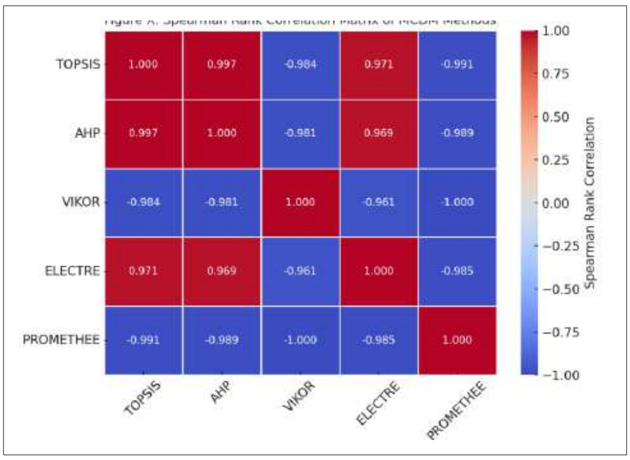

Figure 5. Spearman rank correlation matrix of MCDM methods.

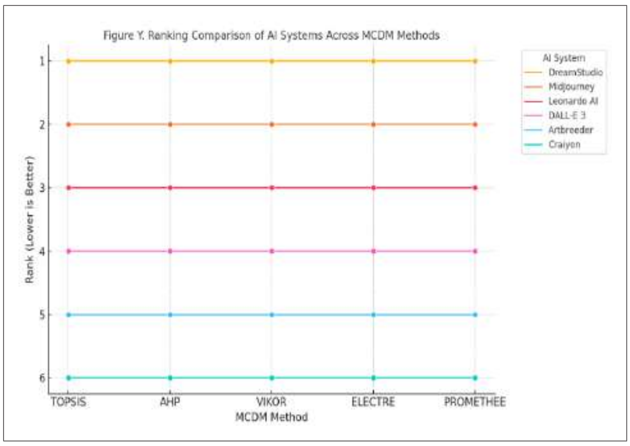

Figure 6. Ranking comparison of AI systems across MCDM methods.

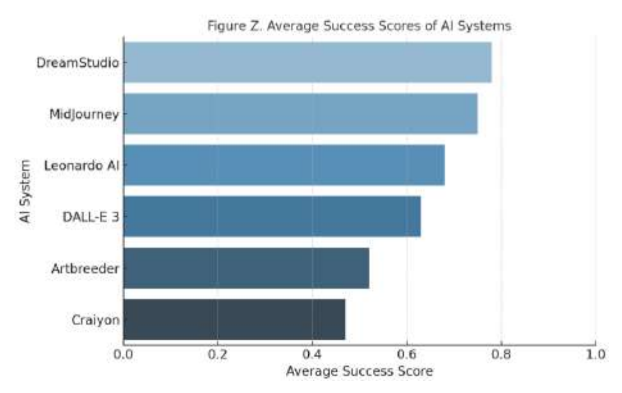

Figure 7. Average success scores of AI systems.

robustness of our findings. However, the inverse relationship observed between VIKOR and PROMETHEE (*r=-1.000*) highlights a critical methodological insight: Different MCDM algorithms can prioritize different aspects of performance (e.g., minimizing regret vs. maximizing net preference flow). This divergence reinforces the value of employing a complementary suite of MCDM methods, as done in this study, to avoid the bias inherent in any single technique and to obtain a more holistic performance profile. A recognized challenge in evaluating commercial generative AI systems is their inherent "black box" nature, which obscures the specific algorithmic processes and training data that underlie image synthesis. While this opacity limits technical interpretability, the output-based, multi-criteria framework employed in this study demonstrates significant practical utility for the design community. By systematically benchmarking AI-generated visuals against established professional standards, the research provides practitioners with an evidence-based rationale for tool selection tailored to specific project requirements. For example, a design phase demanding precise material representation and rigorous spatial logic might benefit more from DreamStudio's controllable, detail-oriented output, whereas a concept development stage seeking inspirational breadth and stylistic flair could leverage MidJourney's compositional strength and aesthetic versatility. Consequently, this approach advances the discourse from general speculation on AI's potential to a nuanced, criterion-driven understanding of its current applicable value in interior architectural workflows. Despite this practical contribution, the study's findings must be considered within its inherent methodological boundaries. This study has several limitations that chart a course for future inquiry. First, the evaluation was inherently static and visual, focusing on image outputs. Critical dimensions of interior architecture—such as user experience, spatial ergonomics, tactile material qualities, acoustics, and the functionality of dynamic elements—were beyond its scope. Second, while the expert panel was professionally diverse, the evaluation may reflect certain demographic (e.g., age range, cultural background) and experiential biases. Factors such as the specific subfields of expertise or individual familiarity with different AI platforms were not controlled for and could influence the scoring, potentially skewing towards aesthetic and cultural biases prevalent in the training data of the AI systems themselves. This underscores a pressing ethical need for more diverse and globally representative datasets.

Future research should therefore pivot towards human-centric and participatory methodologies. Integrating post-occupancy evaluations and sensory feedback could bridge the gap between AI-generated visuals and lived experience. Furthermore, investigating the technical architectures of open-source models (like Stable Diffusion) to develop fine-tuned, domain-specific models for interior architecture presents a promising avenue to move beyond the "black box" and create more transparent, accountable, and culturally sensitive design tools.

CONCLUSION AND IMPLICATIONS

This study presents a comprehensive evaluation of the contributions of text-to-image artificial intelligence (AI) systems to interior architectural design, employing multi-criteria decision-making (MCDM) methods. Among the six analyzed platforms (DreamStudio, MidJourney, Leonardo AI, Artbreeder, Craiyon and DALL-E), DreamStudio and MidJourney emerged as leading performers based on both quantitative analyses and expert assessments. DreamStudio demonstrated superior capabilities in spatial organization, material-texture harmony, and overall compositional coherence. Conversely, MidJourney excelled in generating dynamic and diverse spatial layouts, exhibiting a notable aptitude for visual balance and the skillful application of rich color palettes.

The methodological rigor of the study was enhanced through the application of five distinct and complementary MCDM techniques (TOPSIS, AHP, VIKOR, ELECTRE, and PROMETHEE). The results obtained across these methods generally corroborated the superior performance of DreamStudio and MidJourney. The high positive correlation observed between TOPSIS and AHP (*r=0.997*) indicates a consistent alignment in their evaluation criteria and resulting rankings. Similarly, a strong positive correlation (r=0.989) was found between the dominance scores from ELECTRE and the overall system performance as perceived by the experts. Notably, the strong negative correlation (*r=-1.0*) identified between the VIKOR Q-value and the PROMETHEE net flow highlights the divergent analytical frameworks inherent in these methods, underscoring the importance of methodological diversity in such evaluations. Nevertheless, the overarching trend suggests that DreamStudio and MidJourney currently possess a performance edge over the other systems. The reliability and depth of the study were further augmented by the evaluations provided by an experienced panel comprising 15 architects and 15 interior architects, each with over a decade of professional practice. These seasoned professionals meticulously assessed the AI-generated visuals for their adherence to fundamental interior architectural principles and the components of design. The diverse disciplinary backgrounds of the experts provided a balanced, multifaceted, and comprehensive perspective on how AI tools are perceived and evaluated within the professional design community. However, this study acknowledges certain inherent limitations that offer valuable avenues for future research. The current evaluation process primarily concentrated on the static visual analysis of the AI-generated outputs. Crucial human-centered and functional dimensions of design, such as user experience, spatial ergonomics, the tactile and auditory qualities of materials, or the potential for interactive and dynamic elements within a space, fell outside the scope of this investigation. Furthermore, the emotional resonance, subjective preferences, cultural contexts, and overall personal experiences of end-users in response to these visuals were not incorporated into the analysis. These limitations underscore that the potential contributions of AI to interior architectural design extend beyond mere visual aesthetics, and future research endeavors should invariably address these deeper, multifaceted, and human-centric aspects. Based on the salient findings of this study, several significant and strategic implications for the fields of interior architecture and AI can be articulated.

Firstly, the variable success of AI systems across different design scenarios and evaluation criteria is substantially influenced by the underlying technological infrastructure, the core algorithms employed, the characteristics of the training datasets utilized, and the design of their user interfaces. For instance, the open-source Stable Diffusion architecture underpinning DreamStudio, supported by a broad user base, affords users an unparalleled degree of detailed and precise control over visual outputs, facilitating technically consistent, predictable, and highly customizable results (Rombach et al., 2022). Conversely, MidJourney, with its more proprietary and closed structure, demonstrates a remarkable aptitude for generating creative and original spatial arrangements, achieving striking and harmonious color palettes, and crafting an overall artistic, dynamic, and often surprising visual language (Holmes, 2023). Such fundamental distinctions arise not only from the algorithmic approaches and technical choices of these systems but also from the modes of interaction users engage in, their prompt engineering strategies, and the stylistic preferences inherent in the systems' visual synthesis processes (Oppenlaender, 2023).

Secondly, the inclusion of a correlation matrix among the MCDM methods significantly enhances the methodological robustness and transparency of the evaluation process. Understanding the extent to which different decision-making approaches align, where they yield similar or divergent outcomes, and the underlying assumptions that inform them provides a valuable and solid methodological foundation for future comparative studies in the evaluation of design-oriented AI systems. Such meta-analytical approaches can aid in a better understanding of the strengths and weaknesses of various evaluation frameworks and contribute to the development of more integrated, reliable, and comprehensive assessment models.

Thirdly, and perhaps most critically, despite their creative visualization capabilities, current AI systems exhibit notable limitations in addressing core tenets of interior architectural design, such as spatial logic, structural feasibility, and cultural relevance. Moreover, the risk of aesthetic bias, particularly favoring Western-centric visual norms and aesthetic sensibilities, underscores the urgent need for more diverse, global, and inclusive training datasets. Ethical concerns surrounding originality, intellectual property rights, and the potential displacement of human creativity also necessitate more in-depth and interdisciplinary investigation.

Looking ahead, AI-generated visuals should be positioned as collaborative instruments that extend architectural thinking rather than autonomous design solutions. Future research should move beyond static visual assessment and incorporate user-centered and participatory evaluation frameworks to better capture spatial experience, cultural context, and design intent. Integrating the perspectives of both designers and end users will enable a more comprehensive understanding of how AI tools influence spatial decision-making and design communication. From an interior architectural standpoint, the transformation of AI systems into interactive platforms, capable of testing design alternatives, supporting scenario-based exploration, and facilitating dialogue with clients, represents a critical next step. Overall, the findings indicate that when thoughtfully integrated within architectural workflows and guided by ethical awareness and contextual sensitivity, text-to-image AI systems can meaningfully support creativity, efficiency, and informed design exploration.

ETHICS: This study did not require approval from an institutional ethics committee because it involved no clinical procedures, personal data collection, or intervention with human participants. Participation in the survey was voluntary, based solely on professional expertise evaluations, and did not involve any sensitive or identifying information. All participants contributed anonymously and knowingly to the study.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Albers, J. (1963). *Interaction of Color*. https://static1.squarespace.com/static/58584cab9f7456737a53b75a/t/64a19937919d5e02c85a743e/1688312126264/Josef/+Albers-/+Interaction/+of/+Color.pdf

Arnheim, R. (1954). *Art and visual perception: A psychology of the creative eye*. Univ of California Press.

Artbreeder. (2024). *Artbreeder About*. Artbreeder.

Ashihara, Y. (1986). The aesthetic townscape. *Journal of Aesthetics and Art Criticism, 44*(4), 416–417. https://doi.org/10.2307/429797

Balaban Varol, E., & Varol, A. (2023). Analysis of basic art education course learning outcomes in the context of basic design principles [Temel sanat eğitimi dersi öğrenim çıktılarının temel tasarım ilkeleri bağlamında analizi]. *The Journal of Academic Social Science Studies*, *96*, 183–196. https://doi.org/10.29228/JASSS.72128

Blockchain Council. (2024, April 13). *Leonardo AI: All You Need to Know*. Retrieved April 20, 2024, from https://www.linkedin.com/pulse/leonardo-ai-all-you-need-know-blockchaincouncil-lk2pe/

Boden, M. A. (2018). *Artificial intelligence: A very short introduction*. Oxford University Press. https://doi.org/10.1093/actrade/9780199602919.001.0001

Brown, T. B., Mann, B., Ryder, N., Subbiah, M., Kaplan, J., Dhariwal, P., Neelakantan, A., Shyam, P., Sastry, G., Askell, A., Agarwal, S., Herbert-Voss, A., Krueger, G., Henighan, T., Child, R., Ramesh, A., Ziegler, D. M., Wu, J., Winter, C., & … Amodei, D. (2020). Language Models are Few-Shot Learners. *Advances in Neural Information Processing Systems, 33*, 1–25.

Ceballos, B., Pelta, D. A., & Lamata, M. T. (2018). Rank reversal and the VIKOR method: An empirical evaluation. *International Journal of Information Technology & Decision Making*, *17*(02), 513–525. https://doi.org/10.1142/S0219622017500237

Çeken, B., Ersan, M. Ş., & Tuğrul, D. (2018). Investigation of basic design principles and use of color in market brochures [Market broşürlerinin temel tasarım ilkeleri ve renk kullanımı açısından incelenmesi]. *Journal of Süleyman Demirel University Institute of Social Sciences, 31*, 121–137

Chakraborty, S. (2022). TOPSIS and modified TOPSIS: A comparative analysis. *Decision Analytics Journal*, *2*, 100021. https://doi.org/10.1016/j.dajour.2021.100021.

Chakraborty, S., Chatterjee, P., & Das, P. P. (2023). Elimination Et Choice Translating Reality (Electre). In *Multi-Criteria Decision-Making Methods in Manufacturing Environments* (pp. 111–121). Apple Academic Press. https://doi.org/10.1201/9781003377030-10

Ching, F. D. K. (2007). *Architecture: Form, Space, & Order*. John Wiley & Sons.

Craiyon. (2024). *Craiyon V3*. https://www.craiyon.com/

Deshmukh, S. C. (2013). Preference ranking organization method of enrichment evaluation (promethee). *International Journal of Engineering Science Invention*, *2*(11), 28–34.

Gao, L., Biderman, S., Black, S., Golding, L., Hoppe, T., Foster, C., Phang, J., He, H., Thite, A., & Nabeshima, N. (2020). The pile: An 800gb dataset of diverse text for language modeling. *ArXiv, 00027,* 1–39.

Heerwagen, J., & Leah Zagreus, A. (2005). The human factors of sustainable building design: Post occupancy evaluation of the Philip Merrill Environmental Center. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 49(11), 1–26.

Hill, C., & Matthews, C. (2007). Interior Design. *Journal of Interior Design*, *32*(3), 48–68. https://doi.org/10.1111/j.1939-1668.2007.tb00540.x

Holmes, W. (2023). *The unintended consequences of artificial intelligence and education.* Education International.

Hoser, M., & Köymen, E. (2023). Analysis of Text-to-Image Artificial Intelligence Systems in Terms of Contribution to Interior Coloring. *Bilişim Teknolojileri Dergisi*, *16*(4), 275–283. https://doi.org/10.17671/gazibtd.1252993

Itten, J., & Van Haagen, E. (1973). *The Art of Color: The Subjective Experience and Objective Rationale of Color.* Van Nostrand Reinhold Company.

Kalay, Y. E. (2004). *Architecture's new media: Principles, theories, and methods of computer-aided design*. MIT Press.

Kibert, C. J. (2016). *Sustainable construction: Green building design and delivery*. John Wiley & Sons.

Königk, R. (2011). *Interior design as architecture's' Other' [Master's Thesis]*. University of Pretoria.

Lin, Z., Pathak, D., Li, B., Li, J., Xia, X., Neubig, G., Zhang, P., & Ramanan, D. (2024). Evaluating Text-to-Visual Generation with Image-to-Text Generation. *arXiv, 2024,* 2404.01291. https://doi.org/10.1007/978-3-031-72673-6_20

Liu, P., Yuan, W., Fu, J., Jiang, Z., Hayashi, H., & Neubig, G. (2023). Pre-train, prompt, and predict: A systematic survey of prompting methods in natural language processing. *ACM Computing Surveys*, 55(9), 1–35. https://doi.org/10.1145/3560815

Lupton, E., & Phillips, J. C. (2008). *Graphic design: The new basics*. Princeton Architectural Press.

Midjourney. (2022). *MidJourney User Guide*. https://www.midjourney.com/

Midjourney. (2024). *Prompts*. https://docs.midjourney.com/docs/prompts.

OpenAi. (2024). *ChatGPT*. https://chat.openai.com/

Oppenlaender, J. (2023). A taxonomy of prompt modifiers for text-to-image generation. *Behaviour & Information Technology*, *43*, 1–14. https://doi.org/10.1080/0144929X.2023.2286532

Pallasmaa, J. (2024). *The eyes of the skin: Architecture and the senses*. John Wiley & Sons. https://doi.org/10.1002/9781394200702

Pérez-Núñez, P., Luaces, O., Bahamonde, A., & Díez, J. (2018). *Neural network-based representations for recommendation tasks [Representaciones basadas en redes neuronales para tareas de recomendación]*. https://digibuo.uniovi.es/dspace/bitstream/handle/10651/50961/pereznunez2018.pdf?sequence=1

Pile, J. F. (2007). *Interior Design*. Prentice Hall.

Radford, A., Wu, J., Child, R., Luan, D., Amodei, D., & Sutskever, I. (2019). Language models are unsupervised multitask learners. *OpenAI Blog, 1*(8), 9.

Reynolds, L., & McDonell, K. (2021). Multiversal views on language models. *arXiv, 2021*, 2102.06391.

Rodop, S. (2017). A study of design principles and methods in the context of jewelry design [Tasarım ilke ve yöntemlerinin mücevher tasarımı bağlamında incelenmesi]. *Sanat Tasarim Dergisi*, *8*, 21–27. https://doi.org/10.17490/Sanat.2018.17

Rombach, R., Blattmann, A., Lorenz, D., Esser, P., & Ommer, B. (2022). *High-resolution image synthesis with latent diffusion models*. https://github.com/CompVis/latent-diffusion

Russell, S. J., & Norvig, P. (2016). *Artificial intelligence: a modern approach*. Pearson.

Samara, T. (2008). *Design evolution: theory into practice: a handbook of basic design principles applied in contemporary design*. Rockport Pub.

Sedgwick P. (2014). Spearman's rank correlation coefficient. *BMJ*, *349*, g7327. https://doi.org/10.1136/bmj.g7327

Shi, Y. Q., & Sun, H. (2019). *Image and video compression for multimedia engineering: Fundamentals, algorithms, and standards*. CRC Press. https://doi.org/10.1201/9781315097954

Spence, C. (2020). Senses of place: architectural design for the multisensory mind. In *Cognitive Research: Principles and Implications, 5*(1), 46. https://doi.org/10.1186/s41235-020-00243-4

Wright, F. L. (1975). In the cause of architecture. Architectural record. https://www.architecturalrecord. com/ext/resources/news/2016/01-Jan/InTheCause/Frank-Lloyd-Wright-In-the-Cause-of-Architecture-March-1908.pdf

Megaron, Vol. 21, No. 1, pp. 18–31, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.42027

MEGARON

Article

Comparison of Glazing Types in Terms of Cost Efficiency and Total Energy Consumption

Işıl Iplik[1], Gülçin Gülsüm Konuk Taştan[1], Hızır Gökhan Uyduran[2], Mehmet Nuri İlgürel[1]

[1]*Department of Architecture, Yıldız Technical University Faculty of Architecture, İstanbul, Türkiye*
[2]*Konu Merdiven, İzmir, Türkiye*

ARTICLE INFO

Article history
Received: 27 October 2025
Revised: 11 January 2026
Accepted: 12 January 2026

Key words:
Life cycle cost; investment cost; glazing types; solar low-e coating; argon filling.

ABSTRACT

Energy efficiency in buildings has become an increasingly important design criterion in the context of sustainable architecture. In this context, building envelope components such as window systems must be thoroughly evaluated in terms of energy performance, initial costs, and long-term total cost. This study draws attention to the limitations of the commonly adopted one-dimensional approaches in selecting window glazing systems and offers a comprehensive analysis across three key parameters: Investment cost, energy consumption, and life cycle cost. A total of 64 scenarios are developed for a theoretical residential building located in Istanbul. Comparisons are made across three key performance criteria, taking into account different facade orientations (north/south) and window-to-wall ratios (30%/60%). The results reveal that the optimal window systems differ across the performance criteria, suggesting that selecting a system based solely on energy consumption or investment cost may result in suboptimal or misleading outcomes. Systems with low energy consumption often come with higher investment costs, which may limit the potential to minimize overall life cycle cost. Double-glazed systems with solar low-e coatings tend to yield more favorable life cycle cost outcomes, thanks to their relatively low investment costs and balanced overall performance. The study underscores the importance of adopting a multidimensional approach in window system selection and offers practical guidance to decision-makers aiming for cost-effective design strategies.

Cite this article as: İplik, I., Konuk Taştan, G. G., Uyduran, H. G., & İlgürel, M. N. (2026). Comparison of glazing types in terms of cost efficiency and total energy consumption. Megaron, 21(1):18–31.

This article is based on the PhD Thesis of Işıl İplik, titled "Optimization of the Building Envelope in Dwellings in terms of Sound Insulation and Cost Efficiency", completed at Yıldız Technical University, Department of Architecture.

***Corresponding author**
*E-mail adress: isil.iplik@std.yildiz.edu.tr

INTRODUCTION

Global energy demand continues to rise and is still predominantly met by non-renewable fossil fuels such as coal, oil, and natural gas (International Energy Agency, 2022). These resources are limited in quantity and geographically concentrated in only a few regions, which makes them a major import dependence for many countries (Huo & Peng, 2023; Yadav & Mahalik, 2024). This situation poses a significant long-term risk to energy security, as it increases dependence on external energy sources and heightens supply risks during periods of political and economic instability (Anwar, 2016; Carfora et al., 2022). Buildings contribute to global energy consumption significantly —both directly and indirectly—throughout their life cycle, from construction to demolition (Sharma et al., 2011). As energy control in buildings contributes not only to environmental sustainability goals but also to energy supply security, political authorities have issued directives to encourage energy conservation in the building sector (Gaglia et al., 2017). These measures are intended to limit energy consumption in buildings and reduce the environmental impacts associated with fossil fuel use. In this context, the European Commission (2002) issued the Energy Performance of Buildings Directive (EPBD) to reduce energy consumption in buildings. Under this directive, it has become mandatory in EU member states and candidate countries to determine the energy consumption of buildings during the design phase and to certify them based on their energy performance levels (European Commission, 2002). Parallel to the EPBD, legal regulations on energy efficiency were introduced in Turkey, and the “Regulation on Energy Performance in Buildings” came into force in 2008, making the Energy Performance Certificate mandatory for all buildings (Turkish Standards Institution, 2008).

Since the early 1990s, it has been recognized that the environmental impacts and energy consumption of a product need to be assessed not only during its production or use phases, but across its entire life cycle. This recognition has given rise to the concept of life cycle assessment (LCA) in energy analyses (Carfora et al., 2022; Keoleian, 1993; Tillman et al., 1994). Moreover, the economic dimension of energy efficiency has also gained importance, with the objective of achieving maximum energy performance at the lowest total cost over the life cycle of buildings, and the concept of life cycle cost (LCC) emerged in the early 2000s (Bogenstätter, 2000; Durairaj et al., 2002; Norris, 2001; Sterner, 2000; Wen & Kang, 2001a, 2001b). In light of these developments, the directive issued by the European Commission was revised in 2010, stating that energy-efficient design must be carried out in accordance with cost-optimal scenarios (European Commission, 2010).

Life cycle cost (LCC) is an analytical method used to evaluate the economic performance of a building over its entire life span, encompassing the construction, operation, maintenance, and demolition phases (Dwaikat & Ali, 2018). Since investment cost, maintenance and repair costs, and operating costs are considered collectively in the calculations, energy-efficient design strategies can be evaluated from a long-term economic perspective (Islam et al., 2015).

Residential buildings account for approximately 40% of global primary energy consumption, making them a key focus of energy conservation efforts (Atmaca, 2016). According to sectoral data on final energy consumption provided by the International Energy Agency (IEA), the share of residential buildings in total energy use is 24.6% in Europe (International Energy Agency, 2022) and 21.6% in Turkey (International Energy Agency, 2023). Primary energy consumption in the residential sector mainly arises from heating, cooling, and artificial lighting loads (Turkish Statistical Institute, 2025; U.S. Energy Information Administration, 2025). Transparent elements of the building envelope have a significant impact on energy-efficient design decisions, as they directly influence heating, cooling, and artificial lighting loads through heat losses, daylight gains, and ventilation effects (Hee et al., 2015; Li & Wu, 2025; Wang & Greenberg, 2015). Therefore, appropriate glass selection is a critical factor in energy-efficient building design. However, in architectural practice, glazing selection is often driven by investment cost, while long-term economic and environmental impacts tend to be overlooked.

In the literature, a number of studies addressing life cycle cost focus on only one or two parameters rather than evaluating heating, cooling, and artificial lighting loads comprehensively (Li & Wu, 2025; Solmaz, 2016; Tushar et al., 2022; Villaplana, 2020). The existing research on the transparent components of energy-efficient building envelopes indicates that some scholars investigate design-related features such as window location, orientation, and window-to-wall ratio (WWR) (Baş & Kazanasmaz, 2020; Pathirana et al., 2019; Uç & Dokuzer Öztürk, 2022; Yassin et al., 2017), while others focus on technical parameters including U-value, solar heat gain coefficient (SHGC), daylight transmittance, film coating, and cavity fill (Aguilar-Santana et al., 2020; Cuce et al., 2021; Heydari et al., 2021; Krarti, 2023). Studies investigating the types of glass used in architectural practice generally include a limited number of samples, which hinders a comprehensive analysis of glazing performance under different WWRs, orientations, and technical specifications. While most studies on architectural glazing include a limited number of samples, some focus on advanced or experimental glazing systems that are not commonly used in practice (De Masi et al., 2022; Niu et al., 2022; Sun et al., 2021). On the other hand, studies examining glass used in architectural applications generally include a limited number of samples (Sadrzadehrafiei et al., 2012; Tahmasebi et al., 2011; Yıldız et al., 2011). A substantial proportion of research on the energy performance of glazing focuses on heating and cooling load calculations, while life cycle analyses remain largely overlooked (Cengiz et al., 2024; Hart et al., 2019; Heydari et al., 2021). However, as LCC-focused studies investigate long-term performance, the short-term burden of investment cost is not examined as an independent variable. Nevertheless, investment cost remains a decisive factor in the decision-making process of investors. Therefore, energy performance assessments need to adopt a holistic approach that considers both life cycle cost and investment cost.

In this study, multiple glazing alternatives with different technical properties, commonly used in architectural practice, are compared in accordance with EU directives in terms of life cycle cost, investment cost, and energy consumption, using rooms with varying orientations and window-to-wall ratios (WWRs). The analyzed room is assumed to be located in Istanbul, and its function is defined as residential, a typology in which energy efficiency plays a significant role. This study aims to contribute to energy-efficient design by proposing a cost-effective approach for glass selection and by analyzing the advantages and disadvantages of glazing systems commonly used in architectural practice, considering both life cycle cost and investment cost.

METHODOLOGY

The parameters defined as fixed conditions and design variables are systematically addressed within the scope of this study. In this stage, the volumetric dimensions of the calculation room, facade orientations, window-to-wall ratios (WWRs), wall section types, and insulation thicknesses are defined first, and then the technical properties of the glazing are evaluated.

The calculation room is defined based on the BESTEST (Building Energy Simulation Test) models. This widely applied method for testing and validating building energy simulations also serves as a reference for the development of ASHRAE Standard 140 (Hao et al., 2023; Şahin et al., 2013). In the BESTEST model, room geometry and material properties are deliberately kept as simple as possible to minimize the risk of user error, and rectangular single-zone rooms without internal partitions are analyzed (Taffese, 2012). In this study, the calibrated BESTEST Case 600 model, which is frequently used in scientific research, is utilized (Fan, 2022; Fan et al., 2021; Judkoff & Neymark, 1995; Kyrou et al., 2023; Piccioni et al., 2024; Taveres-Cachat & Goia, 2021; Walker et al., 2022). The BESTEST Case 600 model is diversified in terms of WWR and orientation to evaluate glazing design under different conditions. Analyses are carried out for the south facade, which has the highest potential for solar radiation utilization, and for the north facade, which has the lowest.

The provisions of TS 825:2024 Thermal Insulation Rules for Buildings, issued by the Turkish Standards Institute, are taken into account in determining WWR values. According to the standard, for buildings with a WWR of 60% or higher on heat-loss vertical exterior surfaces, the total thermal transmittance coefficient of the window system (U_{wi}) must not exceed 1.60 W/(m²·K). If this ratio is exceeded, other heat-loss components of the building (e.g., external walls, floors, ceilings) must be designed with U-values that are 25% lower than those recommended in the standard (Turkish Standards Institution, 2024). Considering these provisions, two WWR alternatives—30% and 60%—are evaluated in the study to represent both groups defined in the standard and to reflect common market applications (Figure 1).

In the opaque parts of the model, the simplest wall composition is selected, consisting of exterior plaster, insulation, horizontally perforated brick, and interior plaster layers. The insulation thickness is determined to satisfy the minimum U-values specified in the standard for Istanbul (0.30 W/(m²·K) for 60% WWR and 0.40 W/(m²·K) for 30% WWR). Accordingly, an insulation thickness of 10 cm is used for 60% WWR and 6 cm for 30% WWR (Table 1).

The glazing types included in the study are determined through a systematic analysis of glass systems. The analysis covers glazing configuration (double and triple-glazing), film coatings, cavity fill materials, and glass thicknesses.

Glazing systems are classified into three main groups based on coating type: Uncoated, low-e coated, and solar low-e coated glazing. As preliminary calculations presented in Table 2 show, uncoated glazing does not meet the minimum values recommended in the standard. Therefore, it is not included in the study. Low-e coated glazing reduces heat loss by reflecting long-wave infrared (IR) radiation, thereby contributing to thermal insulation (Mohelnikova, 2009). Solar low-e glazing incorporates multilayer coatings that provide both low-emissivity and solar-control functions simultaneously (Saidur et al., 2008). These glazing systems restrict a significant portion of short-wave solar radiation, which in turn reduces solar gains transmitted to the interior and lowers cooling loads during summer (Dachselt et al., 1982). However, their daylight transmittance and total solar energy transmittance are lower than those of low-e coated glazing (Berardi, 2019). Since both coating types significantly affect energy performance and life cycle cost (LCC), their comparison is considered appropriate within the scope of this study.

In the market, glazing products with thicknesses of 3, 4, 5, 6, 8, 10, and 12 mm are commercially available (Şişecam, 2025). Glass with a thickness of 3 mm is excluded from window applications due to its limited mechanical strength. Glass thicknesses of 5, 8, 10, and 12 mm are generally sold as full sheets rather than by area (m²), which leads to a higher material waste ratio. Therefore, glazing thicknesses of 4 mm and 6 mm are the most commonly used in architec-

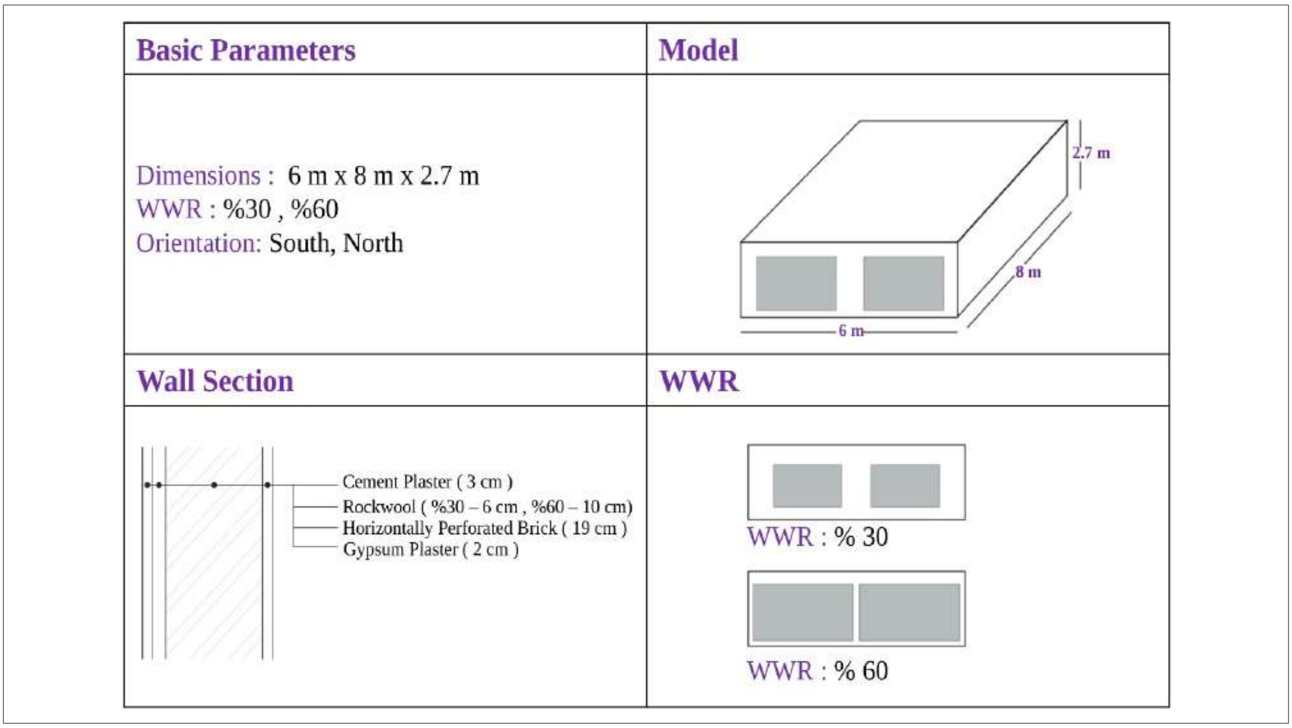

Figure 1. Technical parameters.

tural applications. Accordingly, the study considers glazing combinations formed by 4 mm and 6 mm glass thicknesses to be sufficient for evaluation.

The cavity between glass panes is another critical parameter in double and triple-glazing systems, typically ranging from 9 to 24 mm (Şişecam, 2025). The U-values of the window alternatives decrease as the cavity width increases up to 16 mm and remain nearly constant beyond this point (Table 3). Considering its balanced thermal performance and frequent use under market conditions, a cavity width of 16 mm is deemed appropriate for the evaluation of all glazing combinations.

The cavity between glass panes in glazing systems is typically filled with air or argon to improve thermal insulation performance. The U-value of argon-filled systems is lower than that of air-filled systems (Cuce, 2018). However, the investment cost of argon-filled systems is higher than that of air-filled systems (Aruk, 2023; Şişecam, 2024). Therefore, both cavity fill materials are included in the life cycle cost (LCC) calculations to enable a comparison of their cost and performance characteristics.

Based on these selections, double glazing configurations of '4-16-4' and '6-16-6', which are commonly used in the market, are defined together with the triple-glazing configurations of '4-16-4-16-4' and '6-16-6-16-6', following a parallel logic. By combining low-e and solar low-e coating types with argon- and air-filled cavity alternatives, a total of 16 glazing configurations are defined, consisting of 8 double-glazing and 8 triple-glazing options (Table 4). For each alternative, the thermal transmittance (U-value), solar heat gain coefficient (SHGC), and daylight transmittance are calculated to be used in total energy consumption analyses.

Each glazing alternative is assigned an ID code for reference in the analyses. In these codes, DG denotes double glazing, TG denotes triple-glazing, LEC represents low-e coated glass, and SLEC represents solar low-e coated glass. The numerical values following the glass type indicate the glass thickness in millimeters, whereas the letters A and Ar denote air and argon cavity fillings, respectively. As the cavity thickness is fixed at 16 mm for all alternatives, it is not included in the ID codes. Each ID code is entered into Excel as a data row, and the technical attributes corresponding to that code are recorded in the relevant columns (Table 4).

Energy calculations are performed using the Rhinoceros 8 / Grasshopper platform with the Ladybug and Honeybee v1.8 plugins. The parametric coding process is carried out in four main steps: (i) Defining the fundamental parameters, (ii) introducing the wall and glazing sections into the program, (iii) preparing the energy calculation scripts, and (iv) organizing the cost data (Figure 2).

In the first phase, the simulation model is developed based on the BESTEST Case 600, and the climate data of Istanbul are incorporated into the system. The surfaces of the room are classified as floor, ceiling, and walls. As the building is assumed to be a mid-floor unit, the ceiling and floor surfaces are defined as adiabatic to prevent exposure to outdoor conditions. To represent the two window-to-wall ratios (WWR) under investigation, openings with 30% and 60% WWR are

Table 1. Thermal transmittance coefficient (U) of wall systems with varying insulation thicknesses

Exterior plaster	Insulation	Wall material	Interior plaster	U (W/ m²·K)
2 cm cement plaster	3 cm rockwool	19 cm horizontal perforated brick	2 cm gypsum plaster	0.606
	5 cm rockwool			0.450
	6 cm rockwool			0.399
	8 cm rockwool			0.325
	10 cm rockwool			0.274

Table 2. Thermal transmittance coefficient (U) of uncoated glass types (Şişecam, 2024)

First glass	Cavity width and cavity fill	Second glass	U (W/ m²·K)
4 mm clear glass	16 mm air	4 mm clear glass	2.7
6 mm clear glass	16 mm air	6 mm clear glass	2.7

created in separate layers within the Rhinoceros interface, and north and south orientations are assigned to the room.

The technical data of the wall and glazing sections (e.g., SHGC, daylight transmittance, etc.) are organized in MS Excel and imported into Grasshopper using the keywords defined in the column headers. Since each selected material can be either double- or triple-layered, the number of layers is not identical across all materials. This results in the presence of empty cells in certain data rows within the Excel file.

A custom code is developed to eliminate the empty cells. The physical state of each material (solid or gas) is defined in Grasshopper using the appropriate components. After filtering out the irrelevant data, a material definition block is created using the remaining physical parameters and introduced into the system to model each wall and glazing layer. These layers are then combined to generate the complete wall and glazing sections (Figure 2 – Phase 2).

The Honeybee model, together with the climate data and building operation schedules, is incorporated into Grasshopper to generate the energy calculation scripts. As a result of the simulations, the annual energy demand for heating, cooling, and artificial lighting is obtained (Figure 3).

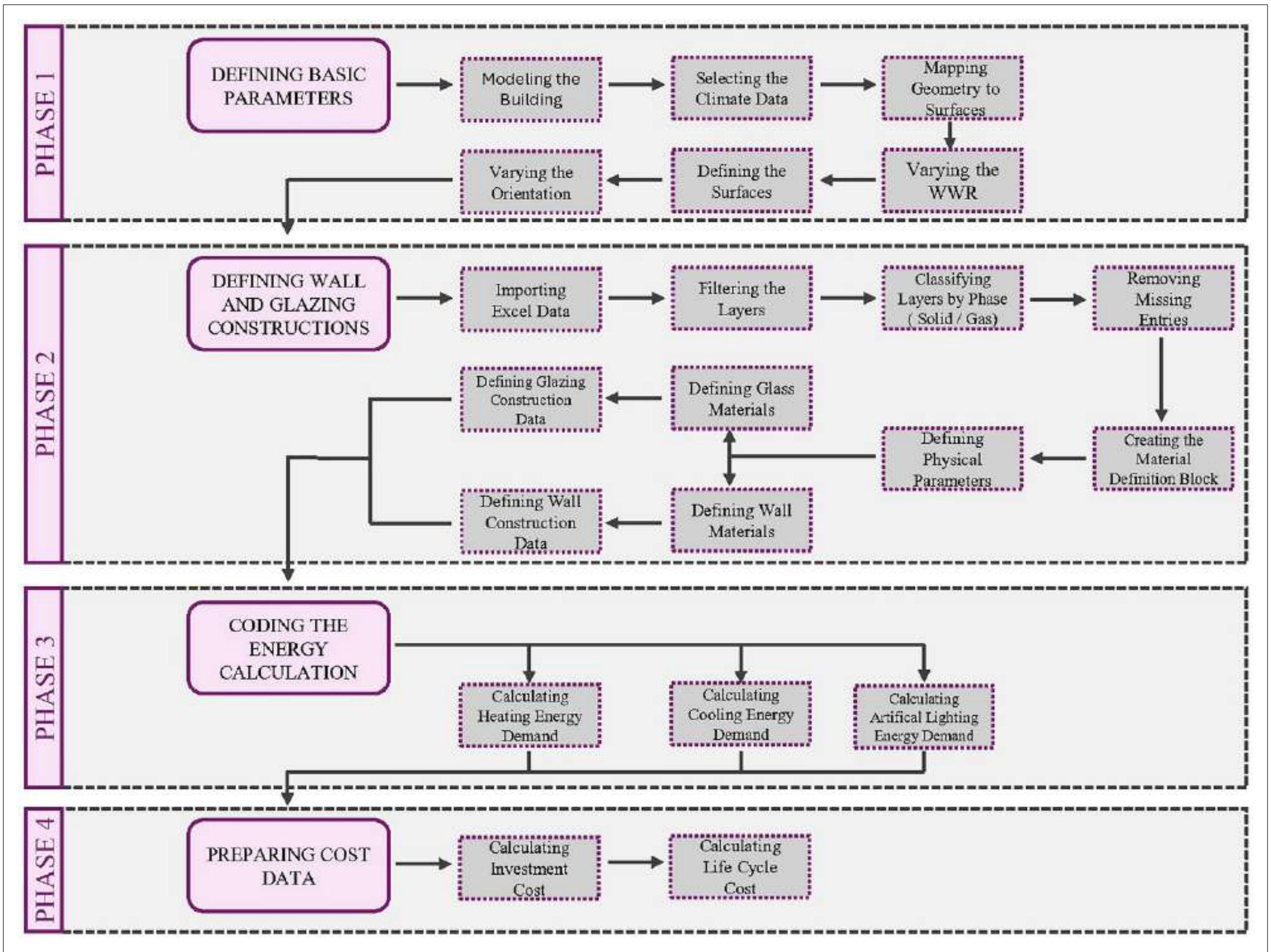

Figure 2. Parametric workflow.

The life cycle cost (LCC) analysis consists of investment, operation, maintenance, repair, and replacement costs (Mangan, 2015; Manioğlu, 2002).

The investment cost (C_i) is calculated using Equation (1), where S_m represents the area of the material and C_m represents the unit cost of the material (in this study, cost per square meter). Since variations in the window-to-wall ratio (WWR) alter the transparent and opaque surface areas, the investment cost is directly affected by these changes. This issue is addressed in the algorithm by adopting a unit-area-based calculation approach. Unit prices of the materials, including labor costs, are obtained from manufacturers and contractors operating in the market. The average of the quotations is used to calculate the investment cost per unit area for each ID code. In Rhinoceros/Grasshopper, a parametric code is developed to calculate surface areas corresponding to different window-to-wall ratios (WWR). The investment cost for each ID code is then determined by multiplying the calculated surface area by the investment cost per unit area.

$$C_i = \sum S_m \; x \; C_m \tag{1}$$

The operation cost is calculated using Equation (2), where C_e denotes the energy cost, CO_f indicates the fuel consumption, C_f defines the fuel cost, P_{PV} represents the amount of energy generated by photovoltaic (PV) panels, and C_{PV} refers to the unit price of the energy produced by PV panels. Since PV systems are not included in this study, the second part of the equation is disregarded. Accordingly, the operation cost is calculated by multiplying the heating, cooling, and artificial lighting loads obtained from the workflow shown in Figure 3 by their respective unit energy prices. The unit energy price, obtained from the local distribution company in Istanbul, is incorporated into the calculation and multiplied by the total energy consumption through an algorithm developed in Rhinoceros/Grasshopper (Energy Market Regulatory Authority, 2025).

$$C_e = \sum\left(CO_f \; x \; C_f\right) - \sum(P_{PV} \; x \; C_{PV}) \tag{2}$$

The maintenance and repair cost ($C_{m,r}$) includes cleaning and preventive maintenance expenses. However, due to the significant variability of these costs even within the same city, sufficient data are not available; therefore, this component is excluded from the scope of the study.

According to the Directive 2010/31/EU of the European Parliament and of the Council (2010), LCC analysis for residential buildings are to be conducted over a 30-year period.

Table 3. Thermal transmittance coefficient (U) for different cavity widths (Şişecam, 2024)

First glass	Cavity width and cavity fill	Second glass	U (W/m²·K)
4 mm low-e coated glass	9 mm air	4 mm clear glass	1.9
	12 mm air		1.6
	16 mm air		1.4
	20 mm air		1.4
	24 mm air		1.4

Table 4. Technical properties of glazing alternatives

ID	System	Cavity fill	U (W/m²·K)	SHGC	Daylight transmittance (%)
DG_LEC_04_A	4-16-4	Air	1.4	0.56	0.79
DG_SLEC_04_A	4-16-4	Air	1.4	0.45	0.72
DG_LEC_04_Ar	4-16-4	Argon	1.1	0.56	0.79
DG_SLEC_04_Ar	4-16-4	Argon	1.1	0.45	0.72
DG_LEC_06_A	6-16-6	Air	1.4	0.55	0.78
DG_SLEC_06_A	6-16-6	Air	1.4	0.44	0.71
DG_LEC_06_Ar	6-16-6	Argon	1.1	0.55	0.79
DG_SLEC_06_Ar	6-16-6	Argon	1.1	0.44	0.71
TG_LEC_04_A	4-16-4-16-4	Air	1.1	0.52	0.72
TG_SLEC_04_A	4-16-4-16-4	Air	1.1	0.41	0.66
TG_LEC_04_Ar	4-16-4-16-4	Argon	0.9	0.52	0.72
TG_SLEC_04_Ar	4-16-4-16-4	Argon	0.9	0.41	0.66
TG_LEC_06_A	6-16-6-16-6	Air	1.0	0.50	0.70
TG_SLEC_06_A	6-16-6-16-6	Air	1.0	0.40	0.64
TG_LEC_06_Ar	6-16-6-16-6	Argon	0.8	0.50	0.70
TG_SLEC_06_Ar	6-16-6-16-6	Argon	0.8	0.40	0.64

Since annual operation costs recur each year throughout the analysis period, the total cost is calculated by considering the present value factor (PVF), as presented in Equation (3). In this formula, *r* denotes the discount rate, and *n* represents the life cycle period (years). In this study, the life cycle period is assumed to be 30 years, with a discount rate of 10%. Accordingly, the present value of the operation cost ($C_{op,t}$) is calculated using Equation (4).

$$PVF = \frac{1}{(1+r)^n} \quad (3)$$

$$C_{op,t} = (C_e \; x \sum_{n=1}^{n} \frac{1}{(1+r)^n}) \quad (4)$$

Finally, the life cycle cost (C_{lc}) is calculated using Equation (5) through a parametric code developed in Rhinoceros/Grasshopper (Figure 4).

$$C_{lc} = C_i + C_{op,t} \quad (5)$$

As a result, the initial investment cost, life cycle cost, and total energy consumption values for 64 scenarios—derived from 16 glazing alternatives (8 double- and 8 triple-glazed alternatives), two transparency ratios (30% and 60%), and two orientations (north and south)—are calculated within a total computation time of 70 minutes using the parametric code developed in Rhinoceros/Grasshopper.

FINDINGS

The scenarios examined within the scope of the study are evaluated in terms of investment cost, total energy consumption, and life cycle cost. For each parameter, the results are listed from the highest- to the lowest-performing systems, and the evaluations are made accordingly. In addition, the performance of different design alternatives—namely, the number of glass panes (double/triple-glazing), coating type (low-e/solar low-e), cavity fill (air/argon), and

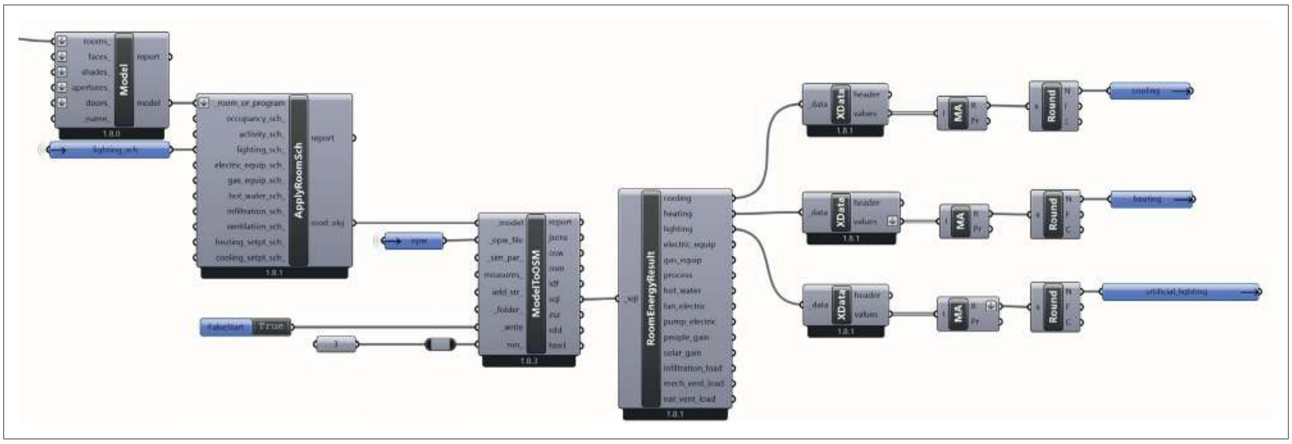

Figure 3. Energy simulation codes for parametric analysis.

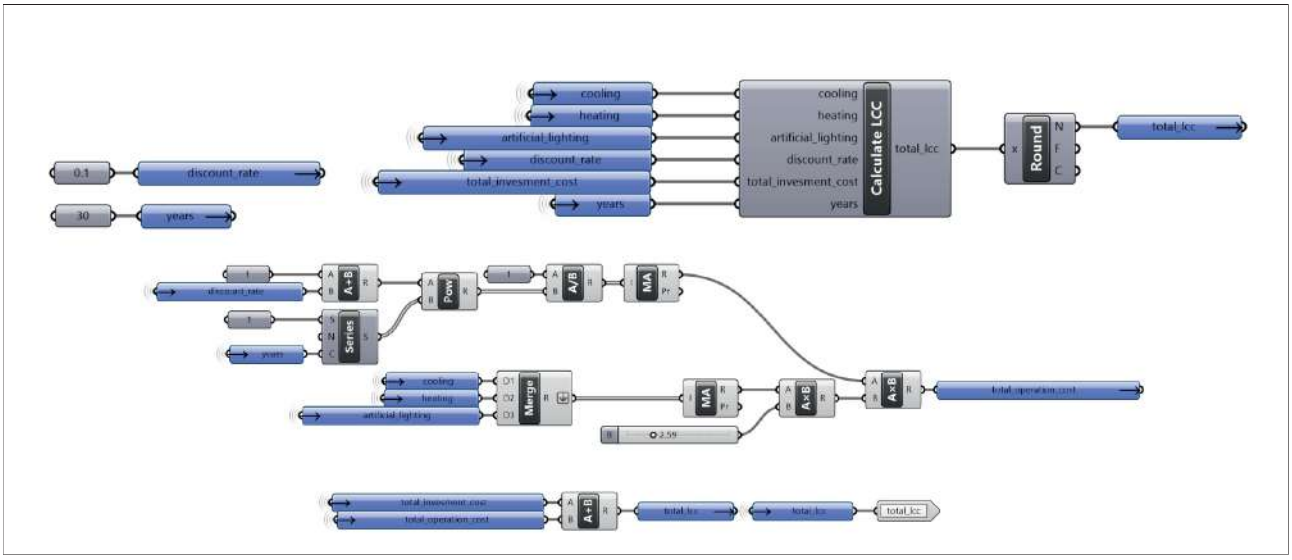

Figure 4. Parametric calculation code for life cycle cost.

glass thickness (4/6 mm)—is analyzed with respect to the selected evaluation parameters.

The investment cost increases significantly for all glazing systems as the window-to-wall ratio increases. In scenarios with a 30% window-to-wall ratio, the investment cost ranges from $390.25 (DG_LEC_04_A) to $805.51 (TG_SLEC_06_Ar), while in the 60% WWR scenarios, this range increases to between $776.17 and $1602.21 for the same systems. Since orientation (north/south) does not have a significant impact on the investment cost, the analyses are conducted based on the technical characteristics of the glazing systems, including the number of layers, coating type, cavity fill, and glass thickness. The number of layers appears to be the most influential factor affecting the investment cost. All double-glazing alternatives are found to be less costly than triple-glazing systems. Subsequently, the effects of cavity fill and glass thickness also appear to have a measurable impact on the investment cost. Although neither variable demonstrates a clear dominance over the other, cavity fill shows a slightly greater influence on the investment cost ranking (Table 5). For example, the sample with the ID code TG_LEC_04_Ar has a higher investment cost than TG_LEC_06_A due to the use of argon as the cavity fill. Thus, despite having a thinner glass thickness, it ranks lower in the investment cost comparison. The component with the least impact on investment cost is the low-e (LEC)/solar low-e (SLEC) film coating. Under all conditions, low-e coated (LEC) alternatives are consistently less costly than solar low-e coated (SLEC) options.

The analysis of the energy performance of window systems reveals that TG_SLEC_06_Ar achieves the highest efficiency in all scenarios, while DG_LEC_04_A shows the lowest performance. Triple-glazing systems provide better energy performance, whereas double-glazing alternatives lead to higher energy consumption. Since buildings constructed in accordance with the TS 825:2024 regulation are generally well-insulated against heat loss, solar low-e coatings tend to stand out in terms of total energy consumption, regardless of whether the orientation is north or south. Regarding the cavity fill variable, argon provides a slight performance advantage over air-filled systems; however, this difference remains limited in terms of energy consumption. A similar pattern is observed for the glass thickness parameter. Although the 6 mm alternatives show a minor improvement in certain scenarios, the differences in annual energy consumption do not indicate a significant advantage.

Energy consumption varies significantly depending on facade orientation and window-to-wall ratio. In scenarios with a 30% window-to-wall ratio, annual energy consumption ranges between 2477 and 2645 kWh on the north facade and between 2663 and 2926 kWh on the south facade. As the window-to-wall ratio increases to 60%, energy consumption rises noticeably, reaching 2814–3194 kWh on the north facade and 3191–3601 kWh on the south facade.

Table 5. Investment cost-based performance ranking

Ranking	ID	Investment Cost ($)	
		30%	60%
1	DG_LEC_04_A	390.25	776.17
2	DG_SLEC_04_A	427.40	850.08
3	DG_LEC_04_Ar	435.27	865.79
4	DG_SLEC_04_Ar	472.45	939.71
5	DG_LEC_06_A	483.14	960.97
6	DG_SLEC_06_A	520.32	1034.89
7	DG_LEC_06_Ar	528.19	1050.57
8	DG_SLEC_06_Ar	565.34	1124.52
9	TG_LEC_04_A	622.51	1238.18
10	TG_SLEC_04_A	659.69	1312.10
11	TG_LEC_06_A	678.25	1349.08
12	TG_LEC_04_Ar	712.62	1417.41
13	TG_SLEC_06_A	715.43	1422.99
14	TG_SLEC_04_Ar	749.77	1491.32
15	TG_LEC_06_Ar	768.36	1528.26
16	TG_SLEC_06_Ar	805.51	1602.21

A comparison of scenarios with the same orientation and window-to-wall ratio reveals significant differences in the energy performance of the window systems. In the 30% window-to-wall ratio scenario, the annual energy consumption difference between glazing types is 263 kWh on the south facade and 168 kWh on the north facade. In the 60% window-to-wall ratio scenarios, these differences become more pronounced, reaching 410 kWh on the south facade and 380 kWh on the north facade. These findings indicate that, for buildings located in Istanbul with different window-to-wall ratios and orientations, an annual energy saving of 6.78% to 13.50% can be achieved through the appropriate selection of number of layers, coating type, cavity fill, and glass thickness (Table 6).

Across all scenarios, the glazing system with the highest performance is DG_SLEC_04_A, whereas the lowest-performing system is TG_LEC_06_Ar. As no significant variations are observed in the rankings with respect to orientation or window-to-wall ratio, glazing systems demonstrate comparable performance across north/south facades and 30%–60% window-to-wall ratios. In other words, while glazing systems exhibit similar performance across different orientations and window-to-wall ratios, their technical properties exert a considerably stronger influence on life cycle cost performance. In terms of the number of glass panes, double-glazing systems demonstrate considerably higher performance than triple-glazing systems. Solar low-e coating and a 4 mm glass thickness stand out with respect to life

Megaron, Vol. 21, No. 1, pp. 18–31, March 2026

Table 6. Total energy consumption-based performance ranking

Ranking	ID (Energy Consumption-kwh.y)			
	30%		60%	
	South	North	South	North
1	TG_SLEC_06_Ar (2663)	TG_SLEC_06_Ar (2477)	TG_SLEC_06_Ar (3191)	TG_SLEC_06_Ar (2814)
2	TG_SLEC_06_A (2680)	TG_SLEC_04_Ar (2492)	TG_SLEC_04_Ar (3227)	TG_SLEC_04_Ar (2851)
3	TG_SLEC_04_Ar (2684)	TG_SLEC_06_A (2501)	TG_SLEC_06_A (3237)	TG_SLEC_06_A (2856)
4	TG_SLEC_04_A (2702)	TG_SLEC_04_A (2517)	TG_SLEC_04_A (3277)	TG_SLEC_04_A (2894)
5	DG_SLEC_06_Ar (2748)	DG_SLEC_06_Ar (2533)	DG_SLEC_06_Ar (3344)	DG_SLEC_06_Ar (2946)
6	DG_SLEC_04_Ar (2758)	DG_SLEC_04_Ar (2536)	DG_SLEC_04_Ar (3360)	DG_SLEC_04_Ar (2960)
7	DG_SLEC_06_A (2770)	TG_LEC_06_Ar (2548)	TG_LEC_06_Ar (3383)	TG_LEC_06_Ar (2987)
8	DG_SLEC_04_A (2785)	DG_SLEC_06_A (2567)	DG_SLEC_06_A (3393)	DG_SLEC_06_A (3009)
9	TG_LEC_06_Ar (2810)	TG_LEC_06_A (2570)	DG_SLEC_04_A (3414)	TG_LEC_06_A (3022)
10	TG_LEC_06_A (2825)	TG_LEC_04_Ar (2572)	TG_LEC_04_Ar (3428)	DG_SLEC_04_A (3024)
11	TG_LEC_04_Ar (2847)	DG_SLEC_04_A (2574)	TG_LEC_06_A (3440)	TG_LEC_04_Ar (3036)
12	TG_LEC_04_A (2857)	TG_LEC_04_A (2594)	TG_LEC_04_A (3490)	TG_LEC_04_A (3074)
13	DG_LEC_06_Ar (2890)	DG_LEC_06_Ar (2606)	DG_LEC_06_Ar (3534)	DG_LEC_06_Ar (3119)
14	DG_LEC_04_Ar (2908)	DG_LEC_04_Ar (2617)	DG_LEC_04_Ar (3548)	DG_LEC_04_Ar (3135)
15	DG_LEC_06_A (2916)	DG_LEC_06_A (2642)	DG_LEC_06_A (3588)	DG_LEC_06_A (3179)
16	DG_LEC_04_A (2926)	DG_LEC_04_A (2645)	DG_LEC_04_A (3601)	DG_LEC_04_A (3194)
Greatest difference (kWh)	263	168	410	380
Greatest difference (%)	9.88	6.78	12.85	13.50

cycle cost performance. The comparison between air- and argon-filled cavities reveals minimal variation, indicating a balanced performance.

At a window-to-wall ratio of 30%, life cycle cost values range from $2785.98 to $3148.10 on the south facade, and from $2607.28 to $2926.22 on the north facade. When the window-to-wall ratio increases to 60%, the range rises to $3741.34–$4393.27 on the south facade and $3411.06–$4057.92 on the north facade. Among the four scenarios that employ the same glazing type, life cycle cost varies between 43.5% and 50.1% (Table 7; Rows 1 and 16). For instance, the life cycle cost of the TG_LEC_06_Ar glazing is $2926.22 in the scenario with a 30% window-to-wall ratio on the north facade, whereas it increases to $3148.10 on the south facade under the same configuration. At a 60% window-to-wall ratio, the corresponding values are $4057.92 on the north facade and $4393.27 on the south facade.

Evaluating each facade orientation and window-to-wall ratio group individually shows that life cycle costs are vary between 12.23% and 18.96%. This variation indicates that, even in scenarios with the same orientation and window-to-wall ratio, the technical components of glazing systems—such as the number of panes, coating type, cavity fill, and glass thickness—have a decisive impact on total cost.

The results reveal that double-glazing systems and 4 mm glass thickness alternatives constitute the most advantageous glazing combinations in terms of investment cost and life cycle cost. While triple-glazing systems and 6 mm glass thickness options demonstrate strong energy efficiency performance, their high investment costs cannot be economically tolerated over the life cycle period. Solar low-e coated glazing systems are achieved as the most advantageous alternatives both in north or south facade orientation. These results demonstrate that, the thermal insulation thicknesses offered in TS825:2024 increases the thermal performance of the building, so the cooling-related energy demand is seems to become more prominent. Argon-filled systems present a disadvantage in terms of investment cost while offering advantages in terms of energy consumption; conversely, the opposite situation applies to air-filled cavity systems. From a life cycle cost perspective, no distinct superiority is observed between the two cavity fill alternatives, and economically advantageous glazing sections can be achieved using either option. Considering all three performance criteria, investment cost, energy consumption and

Table 7. Life cycle cost-based performance ranking

Ranking	ID (Life Cycle Cost - $)			
	30%		60%	
	South	North	South	North
1	DG_SLEC_04_A (2785.98)	DG_SLEC_04_A (2607.28)	DG_SLEC_04_A (3741.34)	DG_SLEC_04_A (3411.06)
2	DG_SLEC_04_Ar (2808.18)	DG_SLEC_04_Ar (2620.15)	DG_SLEC_04_Ar (3785.25)	DG_SLEC_04_Ar (3446.47)
3	DG_SLEC_06_A (2866.21)	DG_LEC_04_A (2630.28)	DG_LEC_04_A (3825.80)	DG_LEC_04_A (3481.13)
4	DG_LEC_04_A (2868.22)	DG_LEC_04_Ar (2651.57)	DG_LEC_04_Ar (3870.55)	DG_LEC_04_Ar (3520.77)
5	DG_SLEC_06_Ar (2892.57)	DG_SLEC_06_A (2694.27)	DG_SLEC_06_A (3908.35)	DG_SLEC_06_A (3583.17)
6	DG_LEC_04_Ar (2898.02)	DG_SLEC_06_Ar (2710.50)	DG_SLEC_06_Ar (3956.50)	DG_SLEC_06_Ar (3619.45)
7	TG_SLEC_04_A (2947.97)	DG_LEC_06_A (2720.60)	DG_LEC_06_A (3999.61)	DG_LEC_06_A (3653.24)
8	DG_LEC_06_A (2952.65)	DG_LEC_06_Ar (2735.17)	DG_LEC_06_Ar (4043.46)	DG_LEC_06_Ar_ (3692.02)
9	DG_LEC_06_Ar (2975.68)	TG_SLEC_04_A (2791.29)	TG_SLEC_04_A (4087.33)	TG_SLEC_04_A (3764.29)
10	TG_SLEC_06_A (2985.08)	TG_LEC_04_A (2819.32)	TG_SLEC_06_A (4164.37)	TG_LEC_04_A (3841.51)
11	TG_SLEC_04_Ar (3022.82)	TG_SLEC_06_A (2833.50)	TG_LEC_04_A (4193.82)	TG_SLEC_06_A (3841.69)
12	TG_LEC_04_A (3042.07)	TG_LEC_06_A (2854.73)	TG_SLEC_04_Ar (4224.21)	TG_SLEC_04_Ar (3905.79)
13	TG_SLEC_06_Ar (3060.77)	TG_SLEC_04_Ar (2860.21)	TG_LEC_06_A (4262.36)	TG_LEC_06_A (3908.35)
14	TG_LEC_06_A (3070.69)	TG_LEC_04_Ar (2890.80)	TG_SLEC_06_Ar (4304.64)	TG_SLEC_06_Ar (3985.36)
15	TG_LEC_04_Ar (3123.72)	TG_SLEC_06_Ar (2903.26)	TG_LEC_04_Ar (4320.53)	TG_LEC_04_Ar (3988.55)
16	TG_LEC_06_Ar (3148.10)	TG_LEC_06_Ar (2926.22)	TG_LEC_06_Ar (4393.27)	TG_LEC_06_Ar (4057.92)
Greatest difference ($)	362.12	318.94	651.93	646.86
Greatest difference (%)	13.00	12.23	17.42	18.96

life cycle cost, together, double-glazed systems with solar low-e coatings and argon or air fills exhibit balanced performance and stand out in terms of life cycle cost.

These findings highlight the importance of incorporating cost data alongside energy performance, emphasizing that energy-focused evaluations alone are insufficient to achieve truly sustainable solutions. The analyses clearly demonstrate the necessity of assessing facade orientation, window-to-wall ratio, glass thickness, and window components in a holistic manner.

CONCLUSION

In recent years, energy efficiency has become one of the core components of sustainability goals and building sector policies. Window components, as integral parts of facade systems, require detailed evaluation since they have a direct impact on energy consumption and often entail high investment and operational costs. In this study, a multidimensional approach is adopted in evaluating window systems, focusing not on a single performance criterion, but on the integration of three key parameters: Investment cost, annual energy consumption, and life cycle cost.

The analyses indicate that energy consumption varies between 2477 and 3601 kWh annually, while life cycle cost ranges from $2607.28 to $4393.27, depending on the glazing configuration. Appropriate selection of glazing systems can provide annual energy savings of 6.78%–13.50%. Architectural parameters such as facade orientation (north/south) and window-to-wall ratio (30%/60%) also influence system performance, although the ranking of glazing alternatives remains relatively stable across these variations.

From an applied perspective, the results provide a clear decision-support framework for architects and investors by demonstrating how commonly used glazing systems perform under varying design conditions in terms of both energy efficiency and long-term cost. The findings reveal that different glazing systems stand out depending on which of the three parameters, investment cost, energy consumption, and life cycle cost, is prioritized. The study demonstrates that, in terms of investment cost, double-glazing systems, 4 mm glass thickness, low-e coatings, and air-filled cavities are the most advantageous options. From an energy consumption perspective, triple-glazing systems combined with 6 mm glass thickness, solar low-e coatings, and argon-filled cavities provide superior performance. With regard to life cycle cost, double-glazing systems, 4 mm glass thickness, and solar low-e coatings emerge as the most favorable alternatives, while air- and argon-filled cavity options exhibit a balanced performance with no clear dominance.

In conclusion, this study indicates that glazing selection in buildings cannot be based solely on investment cost, which is commonly emphasized under free market conditions. Likewise, academic evaluations that focus exclusively on energy consumption may lead to misleading interpretations. Therefore, the results highlight the necessity of adopting a life cycle cost–based approach to ensure appropriate and sustainable glazing selection. The study contributes to the literature by linking parametric energy analysis with life cycle cost assessment, thereby supporting more informed and sustainable facade design decisions.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

ACKNOWLEDGEMENTS: The Author would like to thank Assoc. Prof. Dr. Mehmet Nuri İlgürel, for the supervision of the PHD thesis that this article is based on, in 2026.

REFERENCES

Aguilar-Santana, J. L., Jarimi, H., Velasco-Carrasco, M., & Riffat, S. (2020). Review on window-glazing technologies and future prospects. *International Journal of Low-Carbon Technologies*, *15*(1), 112–120. https://doi.org/10.1093/ijlct/ctz032

Anwar, J. (2016). Analysis of energy security, environmental emission and fuel import costs under energy import reduction targets: A case of Pakistan. *Renewable and Sustainable Energy Reviews*, *65*, 1065–1078. https://doi.org/10.1016/j.rser.2016.07.037

Aruk, Ü. (2023, 23 October). *Glass systems price quote and technical evaluation* [Interview]. İstanbul, Türkiye.

Atmaca, A. (2016). Life cycle assessment and cost analysis of residential buildings in south east of Turkey: part 1—review and methodology. *The international journal of life cycle assessment*, *21*(6), 831–846. https://doi.org/10.1007/s11367-016-1050-8

Baş, H., & Kazanasmaz, T. (2020). Hybrid-model simulations to equilibrate energy demand and daylight autonomy as a function of window-to-wall ratio and orientation for a perimeter office in Izmir. *Megaron*, *15*(4), 537–552. https://doi.org/10.14744/MEGARON.2020.42223

Berardi, U. (2019). Light transmittance characterization and energy-saving analysis of a new selective coating for in situ window retrofit. *Science and Technology for the Built Environment*, *25*(9), 1152–1163. https://doi.org/10.1080/23744731.2019.1620546

Bogenstätter, U. (2000). Prediction and optimization of life-cycle costs in early design. *Building Research Information Research*, *28*(5–6), 376–386. https://doi.org/10.1080/096132100418528

Carfora, A., Pansini, R. V., & Scandurra, G. (2022). Energy dependence, renewable energy generation and import demand: Are EU countries resilient? *Renewable energy*, *195*, 1262–1274. https://doi.org/10.1016/j.renene.2022.06.098

Cengiz, H. T., Zorer Gedik, G., & Korkmaz, E. (2024). Yapıların cam alanlarının enerji etkin iyileştirilmesi ve FDM uygulamasının enerji performansına etkisinin değerlendirilmesi: İstanbul ve Diyarbakır örnekleri. *Gazi University Faculty of Engineering and Architecture Journal*, *39*(4), 2395–2408. https://doi.org/10.17341/gazimmfd.1337385

Cuce, E. (2018). Accurate and reliable U-value assessment of argon-filled double glazed windows: A numerical and experimental investigation. *Energy and Buildings*, *171*, 100–106. https://doi.org/10.1016/j.enbuild.2018.04.036

Cuce, E., Cuce, P. M., & Riffat, S. (2021). Thin film coated windows towards low/zero carbon buildings: Adaptive control of solar, thermal, and optical parameters. *Sustainable Energy Technologies Assessments*, *46*, 101257. https://doi.org/10.1016/j.seta.2021.101257

Dachselt, W. D., Munz, W. D., & Scherer, M. (1982). Low emissivity and solar control coatings on architectural glass. Optical Coatings for Energy Efficiency and Solar Applications, SPIE. https://doi.org/10.1117/12.933252

De Masi, R. F., Festa, V., Gigante, A., Ruggiero, S., & Vanoli, G. P. (2022). The incidence of smart windows in building energy saving and future climate projections. *Energy Reports*, *8*, 283–289. https://doi.org/10.1016/j.egyr.2022.10.222

Durairaj, S. K., Ong, S. K., Nee, A. Y. C., & Tan, R. B. H. (2002). Evaluation of life cycle cost analysis methodologies. *Corporate Environmental Strategy*, *9*(1), 30–39. https://doi.org/10.1016/S1066-7938(01)00141-5

Dwaikat, L. N., & Ali, K. N. (2018). Green buildings life cycle cost analysis and life cycle budget development: Practical applications. *Journal of Building Engineering*, *18*, 303–311. https://doi.org/10.1016/j.jobe.2018.03.015

Energy Market Regulatory Authority. (2025). *Tariff tables for electricity bills* [Elektrik faturalarına esas tarife tabloları]. Retrieved July 20, 2025, from https://www.epdk.gov.tr/Detay/Icerik/3-1327/elektrik-faturalarina-esas-tarife-tablolari

European Commission. (2002). *Energy Performance of Buildings Directive (EPBD).* (2002/91/EC). European Commission: Brussels, Switzerland. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0071:en:PDF

European Commission. (2010). *Energy Performance of Buildings Directive - Recast* (2010/31/EC). European Commission: Brussels, Switzerland. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0031

European Parliament and of the Council. (2010). *Directive 2010/31/EU of the European Parliament and of the Council*. Retrieved December 5, 2021, from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF

Fan, X. (2022). A method for the generation of typical meteorological year data using ensemble empirical mode decomposition for different climates of China and performance comparison analysis. *Energy*, *240*, 122822. https://doi.org/10.1016/j.energy.2021.122822

Fan, X., Chen, B., Wang, S., Zhao, J. R., & Sun, H. J. (2021). An improved typical meteorological year based on outdoor climate comprehensive description method. *Building and Environment*, *206*, 108366. https://doi.org/10.1016/j.buildenv.2021.108366

Gaglia, A. G., Tsikaloudaki, A. G., Laskos, C. M., Dialynas, E. N., & Argiriou, A. A. (2017). The impact of the energy performance regulations' updated on the construction technology, economics and energy aspects of new residential buildings: The case of Greece. *Energy Buildings*, *155*, 225–237. https://doi.org/10.1016/j.enbuild.2017.09.008

Hao, Z., Xie, J., Zhang, X., & Liu, J. (2023). Simplified model of heat load prediction and its application in estimation of building envelope thermal performance. *Buildings*, *13*(4), 1076–1099. https://doi.org/10.3390/buildings13041076

Hart, R., Selkowitz, S., & Curcija, C. (2019). Thermal performance and potential annual energy impact of retrofit thin-glass triple-pane glazing in US residential buildings. *Building Simulation, 12*, 79–86. https://doi.org/10.1007/s12273-018-0491-3

Hee, W. J., Alghoul, M. A., Bakhtyar, B., Elayeb, O., Shameri, M. A., Alrubaih, M. S., & Sopian, K. (2015). The role of window glazing on daylighting and energy saving in buildings. *Renewable and Sustainable Energy Reviews*, *42*, 323–343. https://doi.org/10.1016/j.rser.2014.09.020

Heydari, A., Sadati, S. E., & Gharib, M. R. (2021). Effects of different window configurations on energy consumption in building: Optimization and economic analysis. *Journal of Building Engineering*, *35*, 102099. https://doi.org/10.1016/j.jobe.2020.102099

Huo, J., & Peng, C. (2023). Depletion of natural resources and environmental quality: Prospects of energy use, energy imports, and economic growth hindrances. *Resources policy*, *86*, 104049. https://doi.org/10.1016/j.resourpol.2023.104049

International Energy Agency. (2022). *Total final energy consumption, Europe, 2022*. Retrieved July 02, 2025, from https://www.iea.org/regions/europe/energy-mix

International Energy Agency. (2023). *Total final consumption, Türkiye, 2023*. Retrieved July 2, 2025, from https://www.iea.org/countries/turkiye/energy-mix

Islam, H., Jollands, M., & Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renewable Sustainable Energy Reviews*, *42*, 129–140. https://doi.org/10.1016/j.rser.2014.10.006

Judkoff, R., & Neymark, J. (1995). *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method*. NREL: Colorado, USA.

Keoleian, G. A. (1993). The application of life cycle assessment to design. *Journal of Cleaner Production*, *1*(3–4), 143–149. https://doi.org/10.1016/0959-6526(93)90004-U

Krarti, M. (2023). Optimal optical properties for smart glazed windows applied to residential buildings. *Energy*, *278*, 128017. https://doi.org/10.1016/j.energy.2023.128017

Kyrou, E., Goia, F., & Reith, A. (2023). Current performance and future development paths of transparent PV glazing in a multi-domain perspective. *Energy and Buildings*, *292*, 113140. https://doi.org/10.1016/j.enbuild.2023.113140

Li, X., & Wu, Y. (2025). A review of complex window-glazing systems for building energy saving and daylight comfort: Glazing technologies and their building performance prediction. *Journal of Building Physics*, *48*(4), 496–540. https://doi.org/10.1177/17442591241269182

Mangan, S. D. (2015). *A life cycle approach that can be used to assess the performance of residential buildings in terms of energy and cost efficiency* [Yaşam döngüsü enerji ve maliyet etkinliği açısından konut binalarının performanslarının değerlendirilmesinde kullanılabilecek bir yaklaşım] (Publication No. 363840) [Doctoral dissertation]. Istanbul Technical Univerity.

Manioğlu, G. (2002). *An approach that can be used to determine the appropriate building envelope and operating mode option in terms of energy efficiency in heating and life cycle cost* [Isıtmada enerji ekonomisi ve yaşam dönem maliyeti açısından uygun bina kabuğu ve işletme biçimi seçeneğinin belirlenmesinde kullanılabilecek bir yaklaşım] (Publication No.

127207) [Doctoral dissertation], Istanbul Technical University.

Mohelnikova, J. (2009). Materials for reflective coatings of window glass applications. *Construction and Building materials*, *23*(5), 1993–1998. https://doi.org/10.1016/j.conbuildmat.2008.08.033

Niu, Y., Zhou, Y., Du, D., Ouyang, X., Yang, Z., Lan, W., Fan, F., Zhao, S., Liu, Y., Chen, S., Li, J., & Xu, Q. (2022). Energy saving and energy generation smart window with active control and antifreezing functions. *Advanced Science*, *9*(6), 2105184. https://doi.org/10.1002/advs.202105184

Norris, G. A. (2001). Integrating life cycle cost analysis and LCA. *The international journal of life cycle assessment*, *6*(2), 118–120. https://doi.org/10.1007/BF02977849

Pathirana, S., Rodrigo, A., & Halwatura, R. (2019). Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *International Journal of Energy Environmental Engineering*, *10*(1), 107–120. https://doi.org/10.1007/s40095-018-0295-3

Piccioni, V., Grobe, L. O., Hischier, I., & Schlueter, A. (2024). From layer to building: Multiscale modeling of thermo-optical properties in 3D-printed facades. *Energy and Buildings*, *314*, 114222. https://doi.org/10.1016/j.enbuild.2024.114222

Sadrzadehrafiei, S., Sopian, K., Mat, S., Lim, C. H., Hashiğm, H. S., & Zaharim, A. (2012, 7–9 March). *Potential energy and emission reduction through application of triple glazing*. Proceedings of the 6th International Conference on Energy and Development—Environment—Biomedicine (EDEB'12), Athens, Greece.

Şahin, C. D., Gökçen, G., & Durmuş Arsan, Z. (2013, 17–20 April). *Validity of building energy performance simulations: BESTEST (Building Energy Simulation Test) procedure* [Bina enerji performansı simülasyonlarının geçerliliği: BESTEST (Building Energy Simulation Test) prosedürü] 11. National Installation Engineering Congress, İzmir, Türkiye. https://www.researchgate.net/publication/330347424_Bina_Enerji_Performansi_Simulasyonlarinin_Gecerliligi_BestestBuilding_Energy_Simulation_Test_Proseduru#fullTextFileContent

Saidur, R., Hasan, M. M., Haseeb, A. S. M. A., & Masjuki, H. H. (2008). Energy-efficient optical coating for flat glass. *Journal of Applied Sciences*, *8*(10), 1883–1890. https://doi.org/10.3923/jas.2008.1883.1890

Sharma, A., Saxena, A., Sethi, M., Shree, V., & Goel, V. (2011). Life cycle assessment of buildings: A review. *Renewable Sustainable Energy Reviews*, *15*(1), 871–875. https://doi.org/10.1016/j.rser.2010.09.008

Solmaz, A. Ş. (2016). An approach to identify the optimal solutions in the context of energy and cost criteria for buildings in different climates. *Megaron*, *11*(4), 593–606. https://doi.org/10.5505/megaron.2016.09609

Sterner, E. (2000). Life-cycle costing and its use in the Swedish building sector. *Building Research Information Research*, *28*(5–6), 387–393. https://doi.org/10.1080/096132100418537

Sun, Y., Liu, X., Ming, Y., Liu, X., Mahon, D., Wilson, R., Liu, H., Eames, P., & Wu, Y. (2021). Energy and daylight performance of a smart window: Window integrated with thermotropic parallel slat-transparent insulation material. *Applied Energy*, *293*, 116826. https://doi.org/10.1016/j.apenergy.2021.116826

Şişecam. (2024). *Glasstool*. Retrieved May, 15, 2024, from https://www.glasstool.sisecam.com/tr

Şişecam. (2025). *Düz cam ürün kataloğu*. Retrieved June, 13, 2025, from https://www.sisecam.com/tr/duz-cam-urun-katalogu/sisecam-clear

Taffese, W. Z. (2012, 1-4 May). *Improving accuracy with minimal computational effort through coupled building envelope and CFD model* 7. Biennal Building Simulation Conference of IBPSA (eSim 2012), Halifax, Nova Scotia, Canada. https://publications.ibpsa.org/proceedings/esim/2012/papers/esim2012_A1a.pdf

Tahmasebi, M. M., Banihashemi, S., & Hassanabadi, M. S. (2011). Assessment of the variation impacts of window on energy consumption and carbon footprint. *Procedia engineering*, *21*, 820–828. https://doi.org/10.1016/j.proeng.2011.11.2083

Taveres-Cachat, E., & Goia, F. (2021). Exploring the impact of problem formulation in numerical optimization: A case study of the design of PV integrated shading systems. *Building and Environment*, *188*, 107422. https://doi.org/10.1016/j.buildenv.2020.107422

Tillman, A. M., Ekvall, T., Baumann, H., & Rydberg, T. (1994). Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production*, *2*(1), 21–29. https://doi.org/10.1016/0959-6526(94)90021-3

Turkish Standards Institution. (2008). *Thermal insulation requirements for buildings.* (TS 825). TSE: Ankara, Türkiye.

Turkish Standards Institution. (2024). *Thermal insulation requirements for buildings.* (TS 825). TSE: Ankara, Türkiye.

Turkish Statistical Institute. (2025). *Household final energy consumption statistics, 2022 [Hanehalkı nihai enerji tüketim istatistikleri, 2022]*. Retrieved June 20, 2025, from https://data.tuik.gov.tr/Bulten/Index?p=Hanehalki-Nihai-Enerji-Tuketim-Istatistikleri-2022-53805

Tushar, Q., Bhuiyan, M. A., & Zhang, G. (2022). Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing. *Journal of Cleaner Production*, *330*, 129936. https://doi.org/10.1016/j.jclepro.2021.129936

Uç, B., & Dokuzer Öztürk, L. (2022). Determination of the required window glazing area based on the targeted illuminance in residences. *Megaron*, *17*(1), 68–82. https://doi.org/10.14744/megaron.2021.69782

U.S. Energy Information Administration. (2025). *Energy use in homes*. Retrieved June 20, 2025, from https://www.eia.gov/energyexplained/use-of-energy/homes.php

Villaplana, E. B. (2020). *LCC and LCA for low temperature heating integrated with energy active envelope systems* (Publication No. TRITA-ITM-EX 2020:363) [Master's Thesis, KTH]. Stockholm, Sweden. https://www.kth.se/polopoly_fs/1.1055932.1615223269!/LCC%20and%20LCA.pdf

Walker, L., Hischier, I., & Schlueter, A. (2022). Scenario-based robustness assessment of building system life cycle performance. *Applied Energy*, *311*, 118606. https://doi.org/10.1016/j.apenergy.2022.118606

Wang, L., & Greenberg, S. (2015). Window operation and impacts on building energy consumption. *Energy Buildings*, *92*, 313–321. https://doi.org/10.1016/j.enbuild.2015.01.060

Wen, Y. K., & Kang, Y. J. (2001a). Minimum building life-cycle cost design criteria. I: Methodology. *Journal of Structural Engineering*, *127*(3), 330–337. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:3(330)

Wen, Y. K., & Kang, Y. J. (2001b). Minimum building life-cycle cost design criteria. II: Applications. *Journal of Structural Engineering*, *127*(3), 338–346. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:3(338)

Yadav, A., & Mahalik, M. K. (2024). Does renewable energy development reduce energy import dependency in emerging economies? Evidence from CS-ARDL and panel causality approach. *Energy Economics*, *131*, 107356. https://doi.org/10.1016/j.eneco.2024.107356

Yassin, A. A., Sheta, S. A., & Elwazeer, M. A. (2017). Parametric study on window-wall ratio (WWR) for daylighting optimization in multi-story residential buildings: Case study of an apartment complex in Mansoura City, Egypt. *The Egyptian International Journal of Engineering Sciences Technology*, *4*(3), 21–32. https://doi.org/10.17148/IARJSET.2017.4305

Yıldız, Y., Göksal Özbalta, T., & Durmuş Arsan, Z. (2011). Farklı cam türleri ve yönlere göre pencere/duvar alanı oranının bina enerji performansına etkisi: Eğitim Binası, İzmir. *Megaron*, *6*(1), 30–38. https://jag.journalagent.com/megaron/pdfs/MEGARON_6_1_30_38.pdf

Megaron, Vol. 21, No. 1, pp. 32–41, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.07448

MEGARON

Article

Deep learning-based aesthetic evaluation of detached housing designs using rendered images

Murat As[1], Imdat As[2]

[1]Department of Occupational Health and Safety, Aksaray Üniversitesi, Aksaray, Türkiye
[2]Department of Architecture, İstanbul Teknik Üniversitesi, İstanbul, Türkiye

ARTICLE INFO

Article history
Received: 8 January 2025
Revised: 26 August 2025
Accepted: 16 January 2026

Key words:
Automated scoring; aesthetic assessment; deep learning; human scores.

ABSTRACT

The aesthetic evaluation of architectural computer renderings has traditionally remained subjective and dependent on personal, situational, and cultural factors. Within this research, we investigate if deep learning (DL) can be utilized to provide a scientific data-driven solution for approximating the perceived aesthetics in architecture. Our focus is on standalone house designs and uses a dataset of 1,438 computer-rendered competition entries off the Arcbazar website, assigned a rating by professional architects for visual quality. In this research, "aesthetic evaluation" refers to the numerical scores given to the attractiveness to architectural renderings. Our dataset of renderings was standardized through image preprocessing and paired with averaged expert scores. A supervised convolutional neural network (CNN) regression model was then trained and validated using three-fold cross-validation. Model accuracy was established using standard measures of regression (MAE, MSE, RMSE, and R^2). Results indicate that the model was able to predict aesthetic scores with high validity.
While the findings demonstrate the validity of DL models to evaluate architectural renderings, the following limitations should be pointed out: The dependence on rendered views, assessment of just one building type, and expertise based on raters from one platform. Future research will have to expand on the aspects of differing building types, cultural contexts, and multimodal inputs. The incorporation of explainable AI methods will further assist in identifying which visual features contribute most to aesthetic prediction. This work establishes a proof-of-concept framework for integrating deep learning into architectural evaluation, supporting an extensible system that allows for design competition and decision-making. Apart from predictive scoring, such models are well-suited to be integrated with generative design frameworks that will enable the generation of novel architectural proposals optimized in aesthetic quality.

Cite this article as: As, M., & As, I. (2026). Deep learning-based aesthetic evaluation of detached housing designs using rendered images. Megaron, 21(1):32–41.

*__Corresponding author__
*E-mail adress: ias@itu.edu.tr

Published by Yıldız Technical University, İstanbul, Türkiye

INTRODUCTION

The architectural profession has a long history in developing theories on how to judge built works, for example, in classical antiquity, Vitruvius's *De Architectura* laid out one of the earliest known frameworks for architectural evaluations, emphasizing the principles of *firmitas* (structural stability), *utilitas* (functionality), and *venustas* (aesthetic). These qualities became the building blocks of architectural theory and practice and formed the basis of architectural evaluations for many centuries. In the Renaissance, architects like Palladio defined aesthetic in geometric harmony and proportion. Assessing architectural work has been traditionally done through juried competitions, critical essays, and public opinion surveys. While such approaches are not without value, they are all too often clouded by subjective human judgment and cultural and temporal biases, i.e., evaluating aesthetics is traditionally subjective; we propose a computational approach for detached housing renders.

Recent technological developments may help to overcome some of the limitations of these earlier methods and make it possible for more systematic data-driven approaches to evaluate design. Indeed, evaluating aesthetics in architecture, i.e., visual quality and perceived aesthetic of architectural form, including composition, proportion, and harmony, constitutes one of the most important but inherently subjective issues in design. As artificial intelligence (AI) slowly penetrates modern architectural practice, the need to understand how machine learning (ML) and deep learning (DL) models can assist in quantifying and predicting human-perceived aesthetics has grown. Some research even goes as far as to relate the development of AI in general, to the contribution of aesthetic choices and criteria (Pirozelli & Cortese, 2022). In this paper, we explore the use of DL to predict aesthetic scores for architectural designs with a focus on standalone residential buildings using visual features. We gathered 1,438 images of residential architecture, from Arcbazar.com, an online competition platform, where each building was rated according to aesthetic appeal by regular users, experts, and project-owners.

Our aim is to connect visual architectural features with aesthetic scores with the help of DL models, allowing for a systematic process of design evaluations, i.e. developing a pipeline of preprocessing, convolutional neural networks (CNN) regression modeling, and evaluation metrics. For this purpose, we pre-processed images and standardized them, i.e., create uniform dimensions - and attach human aesthetic scores for a consistent target variable. We developed a DL model and tested it against standard regression metrics, focusing on its potential to predict human scores. The paper is structured as follows: The next section reviews prior work, the methods section describes our methodology, the case study section presents the results of our applied work, the discussion section illustrates the implications, and the conclusion section summarizes our work, discusses limitations and opportunities for future work.

This paper is an early systematic attempt to predict aesthetic scores of detached housing designs using CNN regression, with the ultimate goal to automate the evaluations of aesthetic in a particular design. This opens up new ways in integrating AI into the architectural design workflow and provides an approach for both architects and project-owners to better understand and quantify the visual impact of designs. It has a great potential application in design competitions, e.g., scaling up juries, reducing bias, and supporting smaller firms. We present a DL model, *a baseline framework to bridge subjective human judgments with systematic computational evaluation,* that is trained on human aesthetic scores and offers a robust and scalable framework for evaluating and predicting architectural aesthetic.

BACKGROUND

The use of computational methods in architectural aesthetics has become an important area of research, enabled by the rapidly improving capabilities of AI. Traditionally, aesthetic evaluation is deeply rooted in the cultural, historic, and personal contexts in which it takes place. Nevertheless, recent studies try to quantify aesthetic appeal through computational means with the goal of helping architects, designers, and project-owners reach reliable tools to gauge and foresee the quality of a design. In this section we discuss the theoretical and empirical grounding for AI-powered frameworks for design evaluations.

Aesthetic evaluations have been explored in the domains of psychology, design theory, and architectural practice. Early frameworks, such as those proposed by Vitruvius focused on the triad of structure, function, and aesthetic- aesthetics being a core pillar (Rowland & Howe, 2001). Contemporary theories have extended these ideas to include visual complexity, proportion, symmetry, harmony and contrasting counterparts as critical factors that influence perceived aesthetic (Lorand, 1994; Nasar, 1994). Empirical approaches have also been considered to study human perception of aesthetics (Radwan & Ergan, 2017). For instance, the seminal work of Berlyne (1971) on aesthetic preference implicated arousal potential in the explanation, where humans enjoy stimuli that balance complexity and familiarity. In architecture, such principles are implemented in various design features of a building, from façade composition to materiality and color.

DL models have recently been able to quantify subjective preferences with computational models to extract patterns from visual data (Zhang, 2021; Deng et al, 2017; Elgammal et al, 2017). Traditional methods, which include geometric and rule-based models, have been applied in the assessment of proportions and symmetry within architectural designs

(Stamps, 1999). Such approaches, while successful in respect to particular features, fall short of capturing the holistic nature of aesthetics. DL models have transformed this area of research because they can learn from ‘big data’ without human intervention, e.g., convolutional neural networks (CNNs) have proved to be very effective in a wide variety of image analysis tasks, ranging from object recognition and style transfer to now aesthetic prediction. Several authors have already used CNNs to assess the visual aesthetics of photography (Lu et al., 2014; Murray, 2012), paintings (Li & Chen, 2009), and art (Saleh & Elgammal, 2015). The application of DL to architectural aesthetics remains largely unexplored. In design, there have been a number of pioneering studies, e.g., an early version involved ML to predict the aesthetics of urban scenes based on greenery, openness of the environment, and building texture (Seresinhe et al., 2017), while other works aimed at extracting visual features from building facades to predict human preferences by means of a supervised learning approach.

Recent advances in DL have enabled more involved analyses. For example, Park et al. (2024) use a DL-based framework to assess wall designs by matching visual features with human aesthetic judgments. Their work has demonstrated just how DL models can learn to represent complex visual patterns which determine aesthetic experience. Other work has explored using GANs in conjunction with generative models to generate designs that are optimized for aesthetic appeal and meaningful designs (Huang et al., 2021). The use of crowdsourced data for aesthetic evaluation has also gained prominence. Platforms like (hidden) have provided valuable datasets for analyzing human preferences. By using ratings from diverse participants these datasets offer robust benchmarks for training and validating predictive models.

However, challenges such as subjectivity, cultural biases, and data inconsistency remain important challenges in developing consistent evaluation tools. Despite notable progress, several gaps persist in the application of AI to architectural aesthetics. First, most of the existing research has focused on specific elements, such as facades or urban layouts, without dealing with the holistic evaluation of stand-alone buildings. Westerdahl et al. (2006), compared the evaluation of 3D virtual reality model to the experience of built edifice, and demonstrated the limitations. Second, even though DL models have an excellent ability in visual feature extraction, the interpretability remains problematic for them, hindering their application in practical workflows of architectural design. Finally, the human factor that may relate to cultural context and emotional response has not received its deserved representation within computational models.

In this paper, we use images of architectural built work, sourced from an online competition platform, to establish a robust framework that links visual features with human-perceived aesthetics. We processed and standardized the images and combined them with their ‘aesthetic scores’ to ensure the reliability and generalizability of the findings. We also used cross-validation to reduce overfitting and improve the performance of models on diverse datasets. Our work contributes to the fast-emerging domain of computational aesthetics, by introducing a data-driven approach to aesthetics evaluations in architecture. Using AI as a guide in the design process can help architects and project-owners get insight into the visual impact of the design and encourage innovation and creativity in the profession.

METHODS

In this study, we followed a supervised learning approach, which included: Clearly defined data collection steps, image preprocessing, integration of expert-labeled scores, training a deep learning (DL) regression model, and model evaluation, as shown in Figure 1. We used a dataset of 1,438 residential building images from arcbazar.com, where expert architects rated each building’s visual aesthetic appeal, resulting in a numeric aesthetic score associated with each image. Although computer renderings provide controlled visual consistency they cannot fully replicate material, at-

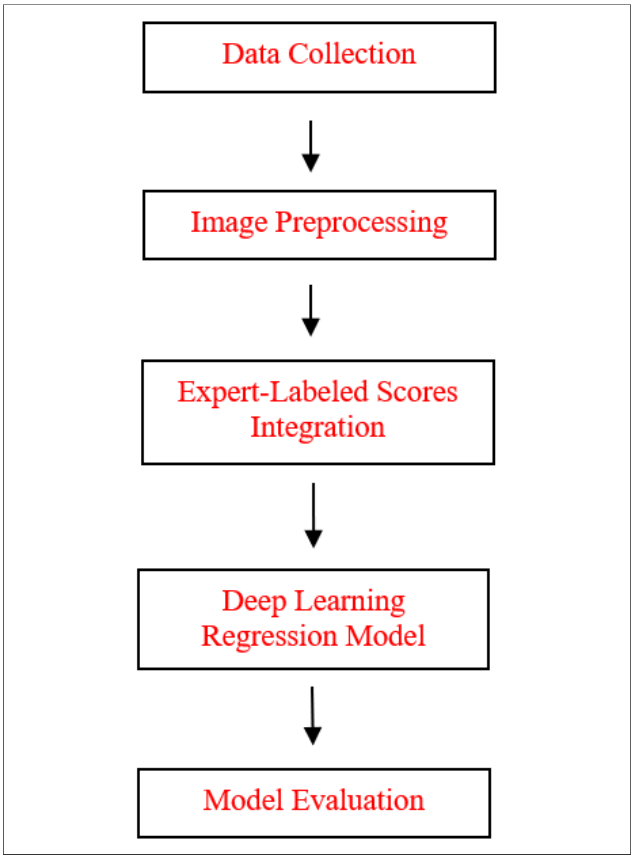

Figure 1. Deep learning-based workflow for aesthetic evaluation of architectural images.

mospheric, or spatial qualities present in photographs of built works. However, they provide standardized views across competitions, they avoid issues with varied photo quality, e.g., lighting, angle, environment, which allowed us to work with a consistent dataset, and also they reflect common practice in architectural competitions, at which state such aesthetic evaluations become significant for stakeholders to make decisions.

We studied the regression relationship between visual features of the buildings and their corresponding beauty scores given by experts. All images were resized to 224×224 pixels and converted to PNG format to ensure consistent dimensions and channel structure for deep learning input. That was a vital step since all images needed to be consistently matched in resolution and color channels for easy training. The target variable was the expert-assigned aesthetic score, averaged per image, used as the regression output for the model.

Image preprocessing steps, such as resizing and format conversion, were performed using Jupyter Notebook scripts. Then, we tested the DL model for predicting the individual building's aesthetic score against its image using a deep neural network in MATLAB.

We used 3-fold cross-validation for performance evaluation to ensure each sample was used in both training and testing phases. This choice was made to balance between computational efficiency and variance estimation, as 3-fold CV offers a good trade-off for relatively moderate-sized datasets. We fine-tuned the model by utilizing initial learning rate limits, i.e. a small number that controls how big a step the model takes when adjusting itself to improve accuracy --too high = unstable, too low = very slow learning, maximum number of epochs, where an epoch means one complete pass of the training data through the model, and adjusting the batch size. We evaluated how well the predicted aesthetic scores matched the ground-truth expert scores using statistical accuracy metrics. We measured model accuracy using MAE, MSE, RMSE, and R^2. MAE gives the average absolute prediction error; MSE penalizes larger errors; RMSE gives an interpretable magnitude of error; and R^2 explains the variance captured by the model. These numbers measure how close the model's predictions are to the real values. Lower error values mean better predictions, and R^2 close to 1 means the model explains most of the variation. In simple terms, these values measure how far the model's predictions are from actual expert scores, with lower values meaning higher accuracy.

To ensure stability and reliability, model performance was evaluated using 3-fold cross-validation, with accuracy variation across folds used to assess generalization. This means the dataset was split into three parts and the model was trained and tested three times so that every sample was used for both purposes. This reduces the risk of overfitting and ensures fair testing. Our deep learning code first constructs input data by linking image paths with a target variable representing the beauty score. The dataset is then randomly shuffled to ensure a balanced distribution between training and testing sets.

The code in Figure 2 splits the data into three parts, with one part being used for testing and the remaining two used for training in each iteration using the cvpartition function. Various performance metrics-MSE, RMSE, MAE, and R^2-are declared as empty arrays. Training and testing for each fold require the proper distribution of datasets in every iteration using the training and test functions. Training the DL model requires using the trainNetwork function. Hyperparameters include learning rate, epoch count, and mini-batch size. These are defined by the trainingOptions function. The model architecture lgraph_1 is predefined as a layerGraph object. Images from both the training and testing datasets are read and converted into 4-dimensional tensors to match the input of the network. Here, the model predicts the images of training and testing datasets using the predict function. For computing the metrics, a custom function called calculate_metrics2 is used to measure the errors between the actual values and predictions made by the model. For each fold, MSE, RMSE, MAE, and R^2 are

```
% K-fold cross-validation parameters
K = 3;
c = cvpartition(size(data, 1), 'KFold', K);

% Create empty arrays for performance metrics
trainMSEs = zeros(K, 1);
trainRMSEs = zeros(K, 1);
trainMAEs = zeros(K, 1);
trainR2s = zeros(K, 1);
testMSEs = zeros(K, 1);
testRMSEs = zeros(K, 1);
testMAEs = zeros(K, 1);
testR2s = zeros(K, 1);

for k = 1:K
  % Split the data into training and testing sets
  train_data = data(training(c, k), :);
  test_data = data(test(c, k), :);

  % Set up training options for the neural network
  options = trainingOptions("adam", ...
    "InitialLearnRate", initialLearnRate, ...
    "MaxEpochs", maxEpochs, ...
    "MiniBatchSize", miniBatchSize, ...
    "Shuffle", "every-epoch", ...
    "Verbose", false);

  % Train the network
  ccnet = trainNetwork(train_data, lgraph_1, options);
```

Figure 2. Code developed for 3-fold cross validating an image-based regression DL model.

computed and stored in corresponding arrays. The final step is reporting the results by calculating all the fold's mean and standard deviation for both the training and testing datasets.

MODELING AESTHETIC EVALUATIONS WITH DEEP LEARNING

This case study is based on design entries submitted to residential architectural competitions hosted on arcbazar.com. Our goal was to develop a DL model that can automatically evaluate architectural design work. We explored the predictive performance of our model using various statistical metrics, e.g., Mean Absolute Error, and R-squared. Model robustness was validated through 3-fold cross-validation, residual analysis, and comparison of predicted vs. actual expert scores.

Figure 3 illustrates the full workflow, from data collection and image preprocessing to model training and final performance evaluation. We trained our DL model with 1438 images from residential competition results at (hidden). Each image had beauty scores from three different types of users, e.g., regular users, expert architects who already won a certain number of competitions, and project-owners who actually launch the competitions. For our study we only used the scores of expert architects, since scores of regular users showed too much variation. The predicted scores closely approximated the actual scores given by expert architects, indicating strong regression performance.

As shown in Table 1, the performance metrics of the model are presented, including MAE (Mean Absolute Error), MSE (Mean Squared Error), RMSE (Root Mean Squared Error), and R^2 (R-squared), which are evaluated using 3-fold cross-validation. MAE measures the average magnitude of errors between predicted and actual values, providing an intuitive indication of model performance. MSE calculates the average of the squared differences between predictions and observations, penalizing larger errors more heavily and making it sensitive to outliers. RMSE, as the square root of MSE, expresses the error in the same units as the target variable, offering a practical interpretation of predictive accuracy. R^2, also known as the coefficient of determination, quantifies the proportion of variance in the dependent variable explained by the independent variables, with values closer to 1 indicating a better fit. Cross-validation, a robust resampling technique, is used to assess model performance by splitting the dataset into multiple folds and alternating between training and validation sets, ensuring that every data point is utilized in both phases. Additionally, the model was trained using an initial learn rate of 0.0005, which controls the step size of weight updates during optimization, with a maximum of 10 epochs, denoting the total number of complete passes through the dataset, and a mini-batch size of 64, specifying the number of samples used per iteration. These training parameters and metrics collectively provide a comprehensive assessment of the model's performance and training configuration.

The metrics used for the training data reflect the model's performance. The MAE, MSE, and RMSE values are relatively low: MAE is 0.3324, MSE is 0.199, and RMSE is 0.4282, indicating high accuracy of the model on the training data. The R-squared (R^2) value is 0.9745, showing that the model explains over 97.45% of the variance in the target variable, demonstrating excellent performance on the training data.

We used the same metrics (MAE, MSE, RMSE, and R^2) to evaluate the model's performance on unseen test data. The errors on the test data are higher than those on the training data, with MAE being 0.7618, MSE 1.2947, and RMSE 1.1377. However, all these values remain within acceptable limits and reflect reasonable generalization capability. The average R^2 value of 0.8340 suggests that the model describes about 83.40% of the variance in the target variable on the test data.

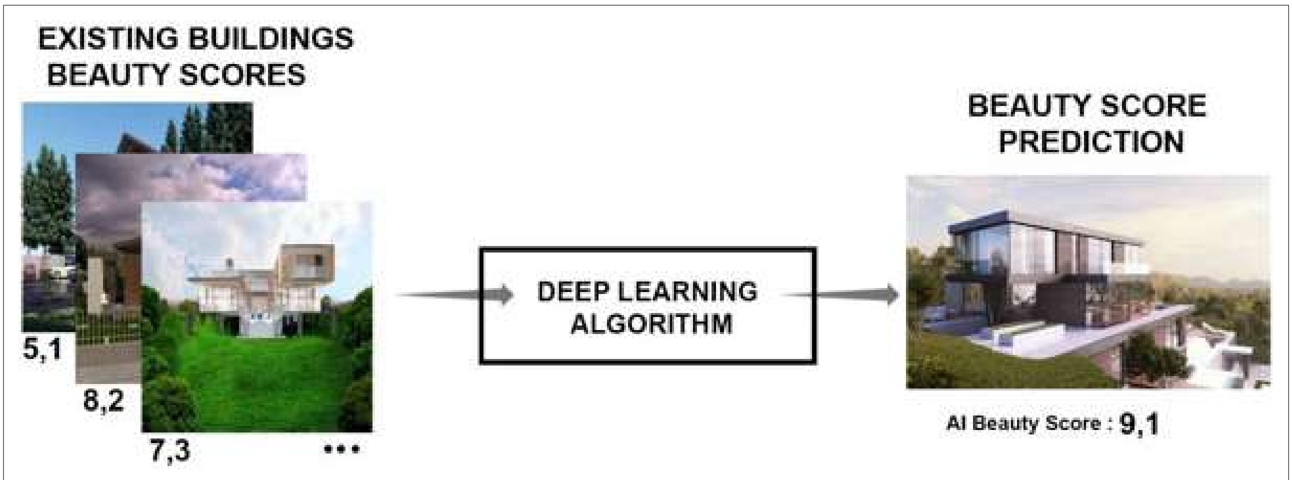

Figure 3. Basic DL workflow for predicting the aesthetic scores of images.

Table 1. Performance Metrics and Hyperparameters of Training and Testing Data Based on Cross-Validation Results

Performance Metrics	Train				Test			
	Mae	Mse	Rmse	R^2	Mae	Mse	Rmse	R^2
Cross_Validation_1	0.2649	0.1140	0.3376	0.9856	0.7383	1.2870	1.1345	0.8293
Cross_Validation_2	0.4651	0.3659	0.6049	0.9534	0.7913	1.2506	1.1183	0.8380
Cross_Validation_3	0.2672	0.1171	0.3422	0.9847	0.7558	1.3465	1.1604	0.8346
Average	0.3324	0.199	0.4282	0.9745	0.7618	1.2947	1.1377	0.8340
Initial Learn Rate	0.0005							
Max Epochs	10							
Mini Batch Size	64							

The cross-validation results also depict a small variance in performance between the best and worst folds, especially with regard to R^2 and MAE. For example, the R^2 values of the test data vary between 0.8293 and 0.8380, meaning that the model performed very well across the different folds. Hence, the model both on the training and testing side performs well.

Considering the R-squared is high-as close to 83.40%- we can conclude that from the test dataset, the actual value of a target variable can be well predicted through the model itself.

The blue circles in the top-left plot of Figure 4 represent the relationship between the observed and predicted values in

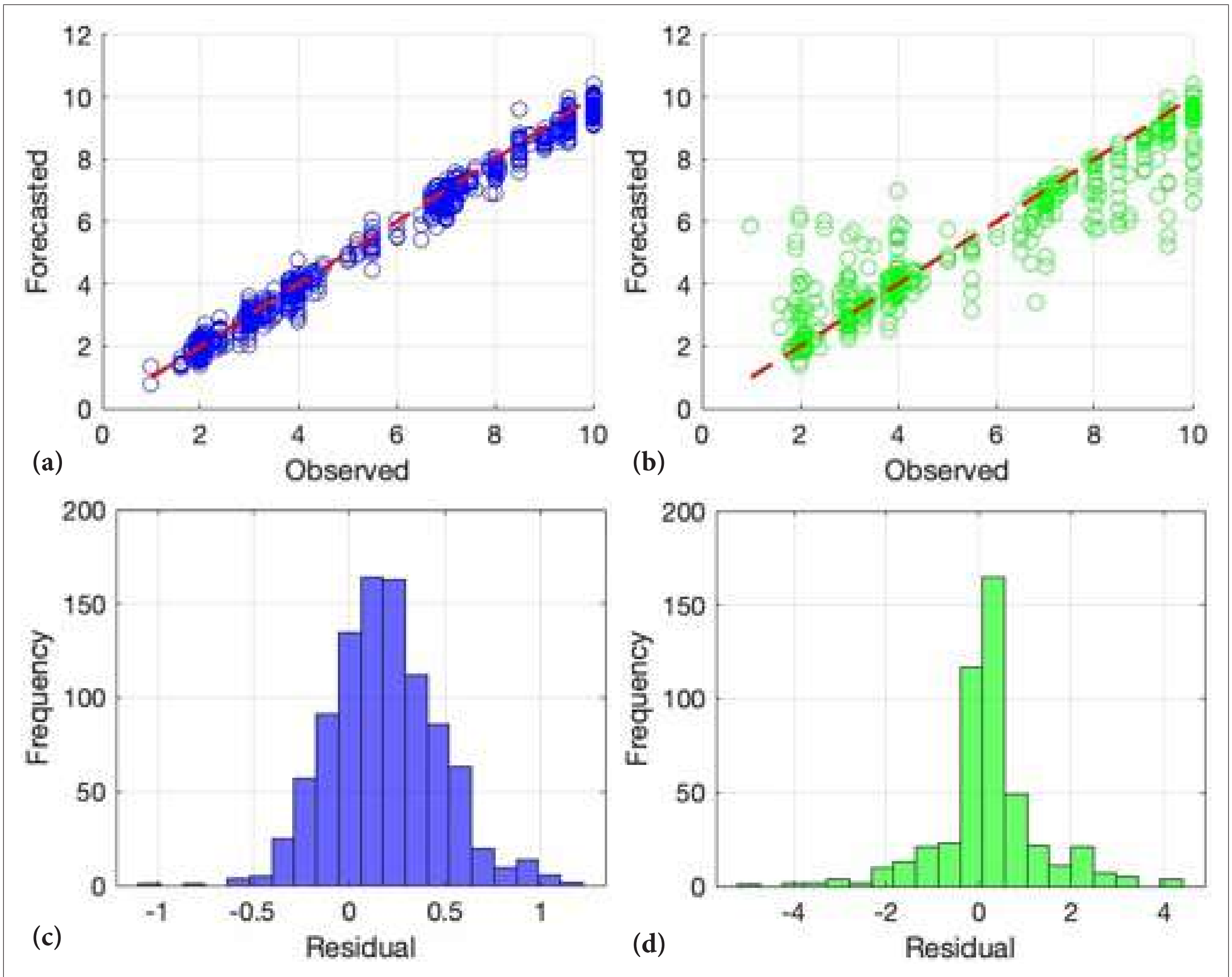

Figure 4. Evaluation of Model Performance: Relationships between predicted and observed values for training **(a)** and test data **(b)**, and histograms of residual distributions for training **(c)** and test data **(d)** are presented.

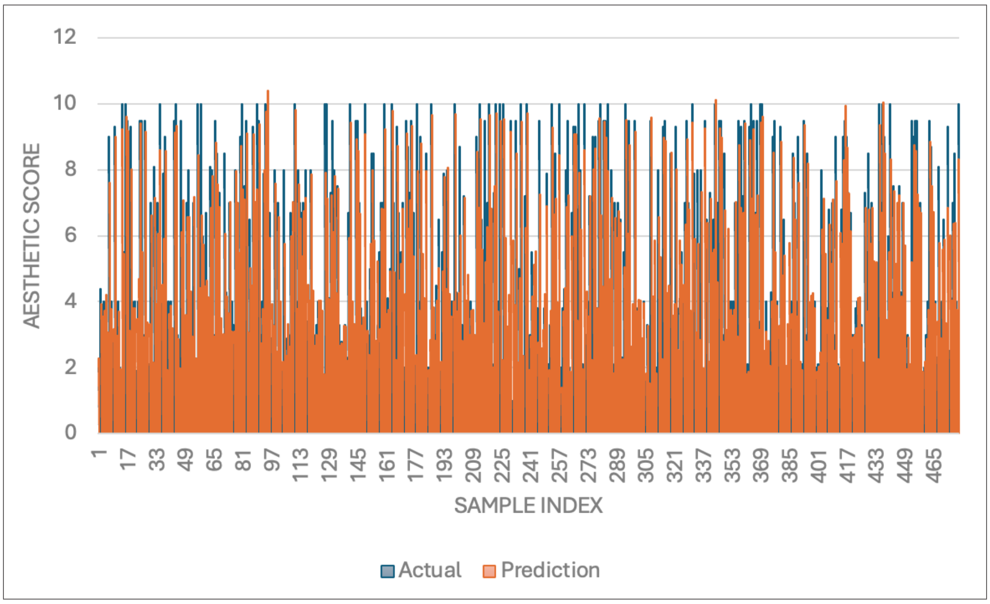

Figure 5. Comparison of actual and predicted values obtained from the test dataset.

the model's training data. The red dashed line indicates the ideal prediction line, y=x, perfect prediction, which allows us to visually assess how accurate the model's predictions are. The predicted values are close to the observed values, which means that the model performs well with the training data. In the top right plot, the green circles show the relation between the predicted and actual values in the test data. Again, the red dashed line represents the ideal line of prediction. The predicted values are generally close to the ones observed, although there is a bit of a more spread in these points compared to the training data. That suggests the performance of the model is somewhat worse when it comes to this test data.

The bottom-left histogram shows the frequency distribution of the model's prediction errors (deviations) on the training data. There is a crowding of the deviations around 0, which means that for the most part, the model predicts without large errors. The shape of the histogram resembles a normal distribution, which suggests that the errors are random and there is no systematic bias in the model. Similarly, the bottom-right histogram presents the distribution of prediction errors on the test data. The deviations are also concentrated around 0 but with a wider spread than for the training data. The errors in the test data are more variable, indicating that the model struggled more when it had to predict new images.

In general, the model shows great performance with the training data. The values are well matched between predicted and observed, and there is very little error. For the test data, as shown in Figure 5, the model performs well with slightly more errors and dispersion – compared to the training data. The graph shows that the actual values, Test_actual, and the predicted values, Test_prediction, are normally on a very similar path and clearly indicate that the model performed well in its predictions. The overall trends within the dataset have been well captured by the model, as reflected in its capability to generate predictions that are

Table 2. Actual and predicted values for the first 20 data points out of a total of 479 observations in the test dataset

Data	Actual	Prediction
1	2.1	2.2773921
2	4.4	3.9213858
3	3.8	3.5455017
4	4	3.7227278
5	3	4.2232203
6	1.8	3.0767283
7	9	7.617538
8	4	3.7764783
9	3	3.174438
10	9.3	9.0082617
11	3.3	2.961113
12	4	3.7118716
13	2	1.961212
14	10	9.245945
15	5.5	5.4527626
16	10	9.619029
17	9.5	9.1773605
18	2.4	3.121088
19	9.3	8.0058241
20	4	3.7962461

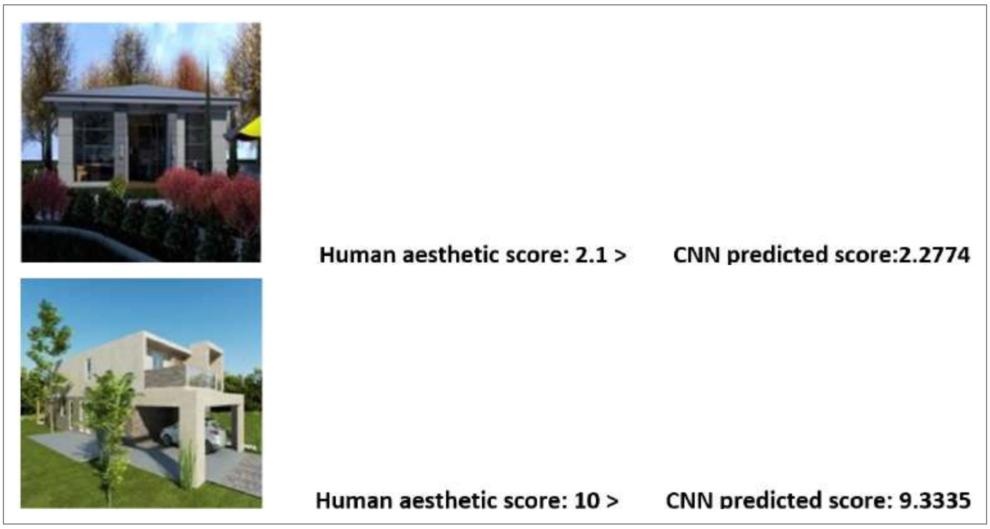

Figure 6. Shows two examples of the home designs scored on (hidden). You see the actual image and its human score, and to its right you see the aesthetic score predicted from our DL model.

largely consistent with the actual values. Notably, the deviations of the model outputs from the actual values are mostly minimal, indicating how reliable the model is.

Overall, as seen in the first image of Figure 6, where the human aesthetic score is 2.1, our deep learning model predicted 2.2774, and for the second image, where the human aesthetic score is 10, it predicted 9.3335. The model shows a great level of accuracy in its predictive performance. Most of the predicted values lie very close to the actual values, which means that the model has grasped the underlying patterns in the data.

These results underpin the high predictive capability of the model and also extend its applicability to more complex datasets or diverse scenarios where its robust performance can be tapped into effectively evaluating built work.

As seen in Table 2, the comparison between actual values and model predictions for the images is presented. The "Data" column represents the image identifier, while the "Actual" column shows the true values or observations, and the "Prediction" column displays the values predicted by the model. For example, for the first image (Data 1), the actual value is 2.1, and the model predicts a value of 2.2773921. Similarly, for Image 2, the actual value is 4.4, while the prediction is 3.9213858, and this continues for the first 20 images. This table demonstrates the closeness of the predicted values to the actual ones for the first twenty test data points.

DISCUSSION

This study demonstrates the potential of convolutional neural networks (CNNs) to reliably predict human-rated aesthetic scores of detached house designs. The results confirm the capability of supervised deep learning algorithms to learn correlations between rendered architectural images and professional judgments. These findings show the potential of computational techniques to enhance traditional architectural evaluations, particularly in settings such as design competitions where large numbers of submissions need to be evaluated.

Human Raters and Evaluation Framework
Professional architects in the Arcbazar competition platform offered aesthetic ground-truth values utilized in the research. These members had verifiable professional background and prior recognition in the site, they collected a certain number of points by winning architectural competitions ran on the platform. All the designs were given numerical scores of visual attractiveness on a continuous scale. While these scores were a good proxy for "aesthetic value," they remain subjective and dependent upon the raters' experience and cultural perspectives. The model was trained on the aggregate of individual opinions rather than objective principles. Future research could benefit from the application of more formal assessment rubrics or several groups of raters to reduce bias.
Complex Patterns and Model Learning

The results demonstrate that CNNs can learn complex architectural features related to perceived aesthetic, which encompass façade composition, proportional relations, rhythm, balance between solid and void, and overall harmony of massing. While such visual characteristics adhere to dominant theories of architectural aesthetic (e.g., Stamps, 1999; Lorand, 1994), the model's outputs were statistically derived –and, not via design rules, codes etc. This demonstrates the power of deep learning to detect implicit aesthetic characteristics embedded in architectural imagery.
Interpretability and Explainable AI
The weakness of this study is interpretability of predictions. Capable though they are, CNNs provide little insight into

which parts of an image or features drive their predictions, researchers work on interpreting and understanding DL models (Samek, 2017). Future work should utilize explainable AI methods, e.g., Gradient-weighted Class Activation Mapping (Grad-CAM) and Shapley Additive Explanations (SHAP) visualizations—to demarcate model attention regions and allow predictions to align with architectural reasoning (Zheng, 2022). Such tools would enable it to determine, for example, if the model gives more importance to façade symmetry, roof ratio, or window arrangement when it generates aesthetic score increment predictions.

Disadvantages of Render-Only Approach

This research is limited in its reliance on rendered representations of individual detached homes. Renders offer standardization and visual simplicity, and they are the main media type when it comes to stakeholders making decision whether to take a design to the next level, i.e., to build it or not. However, they may not convey atmospheric richness, spatiality, or cultural specificity—all factors demonstrated to have an impact on aesthetical perception (Bille, M., & Sorensen, 2016; Herzog & Shier, 2000; Radwan & Ergan, 2017). The data set was also sampled from a single platform and dwelling type. Generalizability of this model demands increased data sets that cover images of built works, mixed building types, and cross-cultural testing.

Implications and Future Directions

Despite these constraints, the work presents a venue for computational aesthetic evaluation in architecture. Directions for future work are:

- Expansion of data sets involving diverse building types and cultural contexts.

- Incorporation of multimodal data (e.g., text description, environmental context, VR/AR spatial experience).

- Incorporation of explainable AI techniques to improve transparency.

- Synthesis of predictive models and generative techniques (e.g., GANs, diffusion models) to enable the creation of new designs optimized for aesthetic value.

With these strategies, AI systems can potentially go beyond acting as predictive critics to become engaged design collaborators, and offer architects and clients new tools for understanding, contrasting, and generating aesthetically informed designs.

CONCLUSION

This paper described a deep learning–oriented methodology for predictive aesthetic judgments of detached house designs from rendered images as input. By training a convolutional neural network on 1,438 human-rated renders, derived from competition submissions on Arcbazar, we demonstrated the feasibility of computational approximation to human-perceived aesthetic with high predictive accuracy. The results confirm the feasibility of subjective judgments' quantification using supervised learning and indicate the potential of artificial intelligence for complementing traditional design evaluation methods.

The study makes three central contributions. First, it lays down a reproducible pipeline to align architectural imagery with aesthetic scores by pre-processing, supervised CNN training, and systematic validation. Second, it suggests detached housing renders as a controlled test case and thereby lays the ground for applying the research to other building types and larger datasets. Third, it identifies opportunities and challenges of computational aesthetics—namely, the need for interpretability, cross-cultural validation, and multimodal design data integration.

There are several limitations to take into account. Render-only images, while standardized, will be unable to capture the full depth of architectural aesthetics that include materiality, spatial experience, and cultural meaning. The dataset's reliance on one platform and set of experts further restricts generalizability. Such limitations indicate that the results need to be taken as proof-of-concept and not a definitive model of architectural aesthetics.

In the future, promising paths include applying explainable AI methods to reveal which visual properties have the most significant impact on predictions, multimodal input such as VR/AR or text descriptions to enhance representational richness, and generative modeling (GANs, diffusion models) to create aesthetically polished design proposals. As a whole, these advancements have the potential to transform AI systems from evaluation tools into generative co-creatives—enhancing human judgment, making it more transparent, and enabling more informed and participatory architectural decision-making.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Berlyne, D. E. (1971). *Aesthetics and psychobiology*. Appleton-Century-Crofts.

Bille, M., & Sørensen, T. F. (2016). *Elements of architecture: Assembling archaeology, atmosphere and the perfor-*

mance of building spaces (1st ed.). Routledge. https://doi.org/10.4324/9781315641171

Deng, Y., Loy, C. C., & Tang, X. (2017). Image aesthetic assessment: An experimental survey. *IEEE Signal Processing Magazine*, *34*(4), 80–106. https://doi.org/10.1109/MSP.2017.2696576

Elgammal, A., Liu, B., Elhoseiny, M., & Mazzone, M. (2017). CAN: Creative adversarial networks, generating "art" by learning about styles and deviating from style norms. *arXiv, 2017,* 07068.

Herzog, T. R., & Shier, R. L. (2000). Complexity, age, and building preference. *Peer Reviewed Articles*, 48, 557–575. https://doi.org/10.1177/00139160021972667

Huang, J., Johanes, M., Kim, F. C., Doumpioti, C., & Holz, G. C. (2021). On GANs, NLP and architecture: Combining human and machine intelligences for the generation and evaluation of meaningful designs. *Technology Architecture and Design*, *5*(2), 207–224. https://doi.org/10.1080/24751448.2021.1967060

Li, C., & Chen, T. (2009). Aesthetic visual quality assessment of paintings. *IEEE Journal of Selected Topics in Signal Processing*, *3*(2), 236–252. https://doi.org/10.1109/JSTSP.2009.2015077

Lorand, R. (1994). Beauty and its opposites. *The Journal of Aesthetics and Art Criticism*, *52*(4), 399–406. https://doi.org/10.1111/1540_6245.jaac52.4.0399

Lu, X., Lin, Z., Jin, H., & Yang, J. (2014). RAPID: Rating pictorial aesthetics using deep learning. In *Proceedings of the 22nd ACM International Conference on Multimedia, 2014,* 457–466. https://doi.org/10.1145/2647868.2654927

Nasar, J. L. (1994). Urban design aesthetics: The evaluative qualities of building exteriors. *Environment and Behavior*, *26*(3), 377–401. https://doi.org/10.1177/001391659402600305

Murray, N., Marchesotti, L., & Perronnin, F. (2012). AVA: A large-scale database for aesthetic visual analysis. *2012 IEEE Conference on Computer Vision and Pattern Recognition, 2012,* 408–415. https://doi.org/10.1109/CVPR.2012.6247954

Park, S. B., Park, J. H., & Jung, S. (2024). Comparative aesthetic assessment of machine learning and human judgment for building wall designs. *Architectural Science Review*, *67*(4), 321–331. https://doi.org/10.1080/00038628.2023.2278500

Pirozelli, P., & Cortese, J. F. (2022). The beauty everywhere: How aesthetic criteria contribute to the development of AI. In *I (Still) Can't Believe It's Not Better! Workshop at NeurIPS 2021* (pp. 69–74). PMLR.

Radwan, A., & Ergan, S. (2017). Quantifying human experience in interior architectural spaces. *ASCE International Workshop on Computing in Civil Engineering, 2017*, 373–380. https://doi.org/10.1061/9780784480830.046

Rowland, I. D., & Howe, T. N. (2001). *Vitruvius: Ten books on architecture*. Cambridge University Press.

Samek, W., Wiegand, T., & Müller, K. R. (2017). Explainable artificial intelligence: Understanding, visualizing and interpreting deep learning models. *arXiv, 2017,* 08296.

Saleh, B., & Elgammal, A. (2015). Large-scale classification of fine-art paintings: Learning the right metric on the right feature. *arXiv, 2015,* 00855.

Seresinhe, C. I., Preis, T., & Moat, H. S. (2017). Quantifying the impact of scenic environments on health. *Scientific Reports*, *5*, 16899. https://doi.org/10.1038/srep16899

Stamps, A. E. (1999). Physical determinants of preferences for residential facades. *Environment and Behavior*, *31*(6), 723–751. https://doi.org/10.1177/00139169921972326

Westerdahl, B., Suneson, K., Wernemyr, C., Roupé, M., Johansson, M., & Allwood, C. M. (2006). Users' evaluation of a virtual reality architectural model compared with the experience of the completed building. *Automation in Construction*, *15*(2), 150–165. https://doi.org/10.1016/j.autcon.2005.02.010

Zhang, J., Miao, Y., & Yu, J. (2021). A comprehensive survey on computational aesthetic evaluation of visual art images: Metrics and challenges. *IEEE Access*, *9*, 77164–77187. https://doi.org/10.1109/ACCESS.2021.3083075

Zheng, Q., Wang, Z., Zhou, J., & Lu, J. (2022). Shap-CAM: Visual explanations for convolutional neural networks based on Shapley value. In *European Conference on Computer Vision* (pp. 459–474). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-19775-8_27

Megaron, Vol. 21, No. 1, pp. 42–61, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.60486

Article

Determining spatial heterogeneity and influencing factors in housing prices with geographically weighted regression method: A case of Erzurum

Cansu Güller

Department of City and Regional Planning, Atatürk University Faculty of Architecture and Design, Erzurum, Türkiye

ARTICLE INFO

Article history
Received: 21 September 2025
Revised: 5 January 2026
Accepted: 6 February 2026

Key words:
Geographical information system; GWR; housing price; spatial autocorrelation; spatial heterogeneity.

ABSTRACT

Understanding the dynamics of the real estate market has emerged as a pivotal concern in urban economics for ensuring sustainable land management and effective investment strategies. The spatial heterogeneity of housing market determinants gives rise to variations in market activity and significant spatial differences in property values. However, global regression models are constrained in their ability to capture this heterogeneity and the spatial autocorrelation of housing prices. The aim of this study is to identify the spatial variability of housing prices and the potential factors influencing them. To this end, the study employs the Geographically Weighted Regression (GWR) model, which enables the analysis of spatial heterogeneity. In addition to conventional structural variables (floor area, age, heating type, number of floors, and floor level), measurable indicators, including network-based accessibility metrics (connectivity, betweenness, and closeness), distance to the central business district, and the remotely sensed Normalized Difference Vegetation Index (NDVI), are integrated into the model. The findings reveal the complexity of the housing market in Erzurum, showing that newly developing peripheral areas form high-priced clusters that reshape the center-periphery dynamics. While structural variables, including floor area and building age, emerge as dominant factors across the city, environmental determinants vary considerably by location. It is noteworthy that network-based accessibility metrics are critical infrastructural variables that shape market heterogeneity. NDVI highlights the decisive role of vegetation density and accessible and functional urban green spaces in determining housing values. In conclusion, this study offers novel insights into the role of environmental and infrastructural metrics in real estate research and provides guidance for policymakers in regulating housing values and designing more sustainable urban planning strategies.

Cite this article as: Güller, C. (2026). Determining spatial heterogeneity and influencing factors in housing prices with geographically weighted regression method: A case of Erzurum. Megaron, 21(1):42–61.

*Corresponding author
*E-mail adress: cansu.guller@atauni.edu.tr

INTRODUCTION

Housing is not merely a physical structure that meets the need for shelter; it is also a fundamental component of individual well-being and social development (Ding et al., 2024). Housing markets, widely recognized as pivotal economic indicators, are closely monitored by governments due to their historic role as catalysts of major economic and financial crises (Güneş & Apaydın, 2022; Wang et al., 2022a). In this context, analyzing the spatial distribution of housing prices provides critical insights for a wide spectrum of urban land management practices, ranging from government regulation to individual purchase decisions, from land-use planning to urban renewal, and from tax and investment strategies to locational suitability assessments (Bovkir & Aydinoglu, 2018). Given that housing price dynamics serve as a strategic source of information for policymakers, market actors, and researchers, housing economics has long remained a central focus of interdisciplinary academic research (Hu et al., 2019; Tchuente & Nyawa, 2022).

Since the advent of housing price modeling and prediction methods, an extensive body of research has emerged, spanning several decades (Wang et al., 2022a). Among these, the Hedonic Price Model (HPM) has been the most frequently employed approach to capture the structural and environmental parameters that shape housing values (Du et al., 2018). Over time, versions of the HPM, originally a global regression model, have been enhanced with GIS-based spatial techniques and, increasingly, machine learning algorithms. These include Support Vector Machines (SVM) (Chen et al., 2017; Ho et al., 2021), Gradient Boosting, and Decision Trees (DT) (Zou et al., 2022; Liu et al., 2024), Random Forest (RF) (Dimopoulos et al., 2018; Adetunji et al., 2022; Ghamrawi & Nat, 2024), Multiple Regression Analysis (MRA) (Lisi, 2019; Yilmazer & Kocaman, 2020; Zhang, 2021), and Artificial Neural Networks (ANN) (Yang et al., 2023; Soegianto et al., 2024). While these models have demonstrated predictive potential across different geographical contexts, the majority fail to adequately account for spatial dependence, assuming instead that the relationship between housing prices and explanatory factors remains constant across the study area. However, the housing market inherently exhibits spatial heterogeneity, with the influence of factors varying across local contexts (Du et al., 2018; Tchuente & Nyawa, 2022; Wang et al., 2022a). For instance, while transportation accessibility may strongly influence prices in peripheral areas, proximity to green spaces may be more decisive in dense urban cores. Such diversity cannot be fully captured by global regression models, often resulting in misinterpretations of market dynamics and the design of unsustainable housing policies (Sisman & Aydinoglu, 2022). This underscores the necessity of employing local regression models capable of accommodating both spatial dependence and heterogeneity.

Against this backdrop, Geographically Weighted Regression (GWR) emerges as a particularly effective tool for capturing spatial variability in the influence of explanatory factors (Wang et al., 2022a; Comber et al., 2023). Unlike global models that apply a single coefficient across the study area, GWR estimates location-specific parameters, thereby illuminating the heterogeneity inherent to housing markets. This methodological advancement enables a more nuanced analysis of the structural and environmental determinants of housing values across diverse geographic contexts (Kopczewska & Ćwiakowski, 2021). Empirical evidence highlights its efficacy: For example, Sisman & Aydinoglu (2022) demonstrated that GWR outperformed Ordinary Least Squares (OLS) in explaining housing prices in Istanbul; Samad et al. (2020) found that local models better captured environmental effects in Malaysia; and Kopczewska & Ćwiakowski (2021), Cellmer et al. (2020), Zhang et al. (2019b), and Tomal (2020) all underscored GWR's capacity to delineate submarkets and explain spatial heterogeneity. Despite this growing body of work, much of the literature has focused on model comparisons. However, there is a clear need for further research to determine the impact of variables that generate spatial heterogeneity on housing prices.

Housing price determinants are broadly grouped into structural and environmental dimensions (Kopczewska & Ćwiakowski, 2021; Sisman & Aydinoglu, 2022; Lu et al., 2023). Structural characteristics typically include housing size, building age, number of floors, and construction quality (Zhang et al., 2019a; Kangallı-Uyar & Keten, 2020; McCord et al., 2020). Environmental factors encompass distance to the city center, presence of green spaces, and accessibility (Du et al., 2018; Zhang et al., 2019b; Wang et al., 2020; Samad et al., 2020). Among these, distance to the city center remains one of the most frequently used variables, serving not only as a measure of location but also as a proxy for functional interaction zones that structure individuals' everyday practices (Zhang et al., 2019a; Tomal, 2020; Kopczewska & Ćwiakowski, 2021). Similarly, green spaces have consistently been shown to enhance property values (Payton & Ottensmann, 2015; Samad et al., 2020), with objective measures such as the Normalized Difference Vegetation Index (NDVI) serving as valuable indicators of environmental quality (Tian et al., 2017).

Accessibility, as a crucial environmental dimension, has often been narrowly defined as proximity to transport infrastructure (Sadayuki, 2018; Yang et al., 2018; Tomal, 2020; Wang et al., 2020). Yet the network topology—including how a street is connected to others or its position within the broader urban network—may better capture residents' spatial perceptions and valuation of housing. Metrics such as betweenness and connectivity offer a more robust representation of accessibility, as evidenced by Law et al. (2017) in the UK, Abdulla & Ibrahim (2023) in Kirkuk, and Liu et al. (2024) in Cardiff. However, these studies primarily relied on global modeling approaches, paying limited attention to local spatial heterogeneity.

More broadly, despite strong evidence that housing prices may vary substantially across neighborhoods due to environmental and locational conditions, spatial heterogeneity has often been addressed only in a limited manner in the existing literature. Conventional global regression models and many machine learning approaches (Ho et al., 2021; Zou et al., 2022; Ghamrawi & Nat, 2024; Soegianto et al., 2024) implicitly assume spatial stationarity and therefore struggle to fully capture spatial dependence. As a result, empirical findings are frequently confined to numerical performance metrics, while the spatially differentiated impacts of key structural, environmental, and accessibility-related determinants remain largely overlooked. In this context, although the application of GWR has increased in recent years, several critical gaps persist. Firstly, much of the GWR-based literature (Samad et al., 2020; Kopczewska & Ćwiakowski, 2021; Cellmer et al., 2020; Zhang et al., 2019b; Tomal, 2020) has focused on comparing the performance of global and local models rather than explicitly identifying which structural, environmental, and accessibility-related variables drive spatial heterogeneity in housing prices. Secondly, accessibility has been functionalized primarily through simple distance-based measures (Tian et al., 2017; Tomal, 2020; Yilmazer & Kocaman, 2020; Sisman & Aydinoglu, 2022; Genc & Colak, 2025; Lee et al., 2025; Soltani et al., 2026), and the impact of street network topology on housing prices remains unclear. Thirdly, empirical evidence combining network-based accessibility indicators with regression models has identified global effects (Porta et al., 2009; Xiao et al., 2016; Kang, 2019; Tan et al., 2019; Ye et al., 2019; Zhang et al., 2021; Chakrabarti et al., 2022; Liu et al., 2024) while neglecting spatially varying effects.

In this context, the objective of this study is to investigate the impact of structural and environmental variables, alongside accessibility indicators derived from Spatial Design Network Analysis (sDNA), on housing prices. To this end, a GWR framework was employed to explicitly incorporate spatial heterogeneity. The contributions of this study are threefold: (i) Identifying the local-scale variations in the effects of structural and environmental determinants of housing prices, (ii) integrating sDNA-based street network accessibility metrics into housing market analysis, and (iii) providing policy-relevant insights that can inform urban planning and decision-making processes. Guided by this objective, the study addresses the following research questions: (1) How do the effects of structural and environmental characteristics on housing prices vary spatially within the city? (2) What is the role of network-based accessibility indicators derived from sDNA in explaining the spatial pattern of housing prices?

From this perspective, Erzurum was selected as the study area because it has the most dynamic housing market, having recorded the highest annual increase in residential real estate prices of any province in Türkiye. In 2024, housing prices in Erzurum rose by 58.04%, more than double the national average of approximately 25% (Endeksa, 2025). Beyond its remarkable price dynamics, Erzurum provides a particularly suitable empirical context for examining spatial heterogeneity in housing markets. The city has a complex urban structure that includes a historic core with an organic urban fabric, as well as regularly and irregularly developed residential areas, newly planned growth areas, and officially designated urban regeneration zones. This pronounced morphological and functional diversity makes Erzurum an analytically rich case for investigating how structural, environmental, and accessibility-related factors shape housing prices in a spatially heterogeneous manner.

LITERATURE REVIEW

Housing prices are shaped by the interplay of supply-demand dynamics and a broad set of structural and environmental determinants (Wang et al., 2025). Within the housing economics literature, these determinants are commonly grouped into two main categories: (i) The physical and structural attributes of housing units and (ii) the locational and environmental characteristics of their surrounding context (Koramaz & Dökmeci, 2012; Uğurlar & Eceral, 2014; Genç & Çolak, 2025). Structural characteristics refer to the intrinsic physical properties of housings, such as floor area, building age, floor level, and the number of rooms and bathrooms, whereas locational and environmental characteristics encompass accessibility to transportation infrastructure, urban services, and green amenities that shape residential quality of life (Brown & Rosen, 1982; Kim et al., 2018; Lieske et al., 2021).

Structural attributes remain among the most consistently employed variables in empirical housing price models. Core physical characteristics, including housing size, age, and internal layout, have long been recognized as fundamental determinants of housing values (Can, 1990; Adair et al., 1996). Beyond these basic attributes, a growing body of research highlights the importance of building and neighborhood level amenities, such as elevators, covered parking, and location within a gated or secure site, which are generally found to exert positive price effects (Türel, 1981; Ebru & Eban, 2011; Ekşioğlu Çetintahra & Çubukçu, 2011; Kördiş et al., 2014; Genç & Çolak, 2025). Collectively, these findings suggest that housing market participants value not only physical space but also amenities that enhance comfort, security, and overall residential well-being.

Floor level constitutes another structural variable that has received substantial attention in the literature. Numerous empirical studies report a positive and linear relationship between floor level and housing prices, often interpreted as reflecting privacy and reduced exposure to street-level disturbances (Hui et al., 2007; Cho et al., 2009; Du et al., 2018; Xiao et al., 2019; Yılmazer & Kocaman, 2020). However, this relationship is not universally linear. Chau et al. (2007), employing a Box-Cox transformation model, demonstrated that the price premium associated with higher floors varies according to contextual attributes such as scenic views. In housings lacking a view, marginal price gains diminish as floor level increases, whereas in units with a view, each additional floor generates a substantial price premium. These findings underscore the spatially heterogeneous nature of floor level effects and indicate that global linear specifications may fail to fully capture such localized dynamics.

Relatedly, the total number of floors in a building has been identified as an additional factor influencing housing prices. Several studies emphasize that high-rise developments may exert downward pressure on prices, particularly due to their association with higher density, crowding, noise exposure, perceived crime risk, and unfavorable microclimatic conditions. Wong et al. (2011) showed that, ceteris paribus, apartments in taller and denser buildings tend to transact at lower prices than those in shorter structures. Evidence from East Asian cities further suggests that clusters of high-rise buildings can exacerbate thermal discomfort by restricting natural ventilation and daylight access, thereby negatively affecting housing values (Li et al., 2018). Conversely, other studies report positive price effects associated with taller buildings, often reflecting prestige or panoramic views in specific urban contexts (Alkan Gökler, 2017; Kim & Tepe, 2026). Together, these mixed findings highlight the context-sensitive nature of vertical development and building density effects.

At finer spatial scales, housing prices emerge as the outcome of spatially varying processes in which location-specific attributes play a decisive role (Goodman, 1978; Simpson, 1992). A substantial portion of this literature is grounded in classical monocentric urban models, which posit that housing and land prices decline with increasing distance from the central business district (CBD) due to rising travel time and commuting costs (Alonso, 1964; Mills, 1972; Muth, 1969; De Palma et al., 2005). However, as metropolitan regions have increasingly evolved toward polycentric urban structures, the explanatory power of distance to CBD alone has weakened (Koramaz & Dökmeci, 2012). The expansion of automobile dependence, the decentralization of employment and services, and comparatively lower land costs in peripheral subcenters have complicated the traditionally assumed negative distance-price gradient.

Within this context, accessibility indicators, particularly proximity to highways and major transportation corridors, have become widely used in housing price studies (Srour et al., 2002; Tomal, 2020; Yılmazer & Kocaman, 2020; Genç & Çolak, 2025; Soltani et al., 2026). While improvements in transportation infrastructure can enhance accessibility and thereby increase housing values (Tsai, 2018), the literature also documents substantial negative externalities associated with living near main roads, including noise pollution, air quality degradation, and traffic congestion (Gan et al., 2021). For instance, empirical evidence from Utah indicates that these negative effects may outweigh accessibility benefits in certain contexts (Tian et al., 2017). Accordingly, prior studies report both positive and negative accessibility effects separately (Porta et al., 2009; Xiao et al., 2016; Tian et al., 2017; Kang, 2019; Abdulla & Ibrahim, 2023; Liu et al., 2024), suggesting pronounced spatial variability and highlighting the limitations of global modeling approaches that impose a single coefficient across space.

More recently, walkability has emerged as a prominent spatial determinant of housing demand and property values. Walkable urban environments are associated with health, environmental, and social benefits, which can be capitalized into higher housing prices (Kim & Kim, 2020; Huang et al., 2024). Empirical studies increasingly document positive associations between neighborhood-level walkability and housing values (Luo et al., 2025). While early research relied primarily on morphological indicators such as intersection density and block length, recent studies have emphasized network-based centrality measures, particularly closeness and betweenness, to more accurately capture pedestrian accessibility and movement potential (Zhang et al., 2021; Chakrabarti et al., 2022; Liu et al., 2024). Nevertheless, the majority of this literature continues to rely on global regression frameworks, which remain limited in their ability to detect spatially varying effects.

Visual and environmental attributes, particularly urban vegetation, have also gained increasing attention in housing price research (Aboelata & Sodoudi, 2019; Soltani et al., 2026). Among these, the NDVI has become one of the most widely used remote sensing indicators for quantifying urban green cover (Franco & Macdonald, 2018; Kim & Kim, 2020; Zambrano-Monserrate et al., 2021). Higher NDVI values generally indicate denser and healthier vegetation and are associated with improved air quality, urban heat island mitigation, and noise reduction (Strohbach et al., 2012; Haaland et al., 2015), as well as positive mental health and life satisfaction outcomes (Belcher & Chisholm, 2018; Wang et al., 2025). However, the effect of green amenities on housing prices is not uniform; prior studies emphasize that the magnitude and direction of this effect depend on contextual factors such as perceived safety, maintenance quality, and actual usage patterns (Chen & Jim, 2010), further underscoring spatial heterogeneity.

Table 1 synthesizes the key variables of prior studies on housing price determinants. Overall, the literature demonstrates that both structural and environmental variables exhibit spatially heterogeneous effects, with varying magni-

Table 1. Summary of empirical studies on structural, environmental, and network-based determinants of housing prices

Variable	
Floor area	Türel, 1981; Koramaz & Dökmeci, 2012; Alkan Gökler, 2017; De Araujo & Cheng, 2017; Belcher & Chisholm, 2018; Yuan et al., 2018; Liu et al., 2019; Xiao et al., 2019; Gu et al., 2021; Barnes et al., 2025; Genc & Colak, 2025; Wang et al., 2025; Soltani et al., 2026
Number of rooms	Türel, 1981; Selim, 2009; Alkan Gökler, 2017; Belcher & Chisholm, 2018; Samad et al., 2020; Yilmazer & Kocaman, 2020; Sayın et al., 2022; Ben et al., 2023; Huang et al., 2024; Genc & Colak, 2025; Soltani et al., 2026
Age of building	Türel, 1981; Ebru & Eban, 2011; De Araujo & Cheng, 2017; Liu et al., 2019; Xiao et al., 2019; Kim & Kim, 2020; Gu et al., 2021; Sayın et al., 2022; Ben et al., 2023; Huang et al., 2024; Barnes et al., 2025; Genc & Colak, 2025; Kim & Tepe, 2026; Soltani et al., 2026
Number of floors	Alkan Gökler, 2017; De Araujo & Cheng, 2017; Belcher & Chisholm, 2018; Sayın et al., 2022; Huang et al., 2024; Genc & Colak, 2025; Wang et al., 2025; Kim & Tepe, 2026
Floor level	Kördiş et al., 2014; Du et al., 2018; Sadayuki, 2018; Xiao et al., 2019; Tomal, 2020; Yilmazer & Kocaman, 2020; Genc & Colak, 2025
Number of bathrooms	Alkan Gökler, 2017; Du et al., 2018; Kangallı-Uyar & Keten, 2020; Sayın et al., 2022; Sisman & Aydinoglu, 2022; Genc & Colak, 2025; Lee et al., 2025; Kim & Tepe, 2026
Heating type	Selim, 2009; Ebru & Eban, 2011; Ekşioğlu Çetintahra & Çubukçu, 2011; Alkan Gökler, 2017; Sayın et al., 2022; Ben et al., 2023; Genc & Colak, 2025
Covered parking availability	Selim, 2009; Ebru & Eban, 2011; Kangallı-Uyar & Keten, 2020; Tomal, 2020; Kopczewska & Ćwiakowski, 2021; Genc & Colak, 2025
Gated community	Ebru & Eban, 2011; Ekşioğlu Çetintahra & Çubukçu, 2011; Kördiş et al., 2014; Sayın et al., 2022; Genc & Colak, 2025
Smart home	Sadayuki, 2018; Kangallı-Uyar & Keten, 2020
Elevator availability	Türel, 1981; Selim, 2009; Kördiş et al., 2014; Liu et al., 2019; Tomal, 2020; Yilmazer & Kocaman, 2020; Gu et al., 2021; Sisman & Aydinoglu, 2022; Genc & Colak, 2025
Furnished	Ekşioğlu Çetintahra & Çubukçu, 2011; Kangallı-Uyar & Yayla, 2016; Önder & Turgut, 2018
Distance to CBD	Türel, 1981; Koramaz & Dökmeci, 2012; Belcher & Chisholm, 2018; Du et al., 2018; Yuan et al., 2018; Liu et al., 2019; Xiao et al., 2019; Tomal, 2020; Sayın et al., 2022; Huang et al., 2024; Liu et al., 2024; Genc & Colak, 2025; Lee et al., 2025; Kim & Tepe, 2026; Soltani et al., 2026
NDVI	Franco & Macdonald, 2018; Kim & Kim, 2020; Zambrano-Monserrate et al., 2021; Soltani et al., 2026
Street network connectivity	Abdulla & Ibrahim, 2023; Abdulla et al., 2023
Betweenness centrality	Porta et al., 2009; Xiao et al., 2016; Kang, 2019; Tan et al., 2019; Ye et al., 2019; Zhang et al., 2021; Chakrabarti et al., 2022; Liu et al., 2024
Closeness centrality	Porta et al., 2009; Xiao et al., 2016; Kang, 2019; Tan et al., 2019; Zhang et al., 2021; Chakrabarti et al., 2022

tudes and directions across urban contexts. Despite this, a large share of empirical research continues to rely on global models that assume spatial stationarity, thereby neglecting localized relationships. To address this gap, the present study adopts a GWR framework to estimate location-specific parameters and incorporates network-based accessibility indicators derived from sDNA, enabling a more realistic representation of urban connectivity and mobility potential than conventional distance-based measures.

MATERIALS AND METHOD

Study Area

Erzurum's urban development historically reflects different planning approaches (Figure 1a). The city's earliest developed areas form its historical core and present-day city center, exhibiting a predominantly concentric development pattern until the 1950s. Following this period, urban expansion shifted toward a more linear form, largely structured along main transportation axes (Çamur et al., 2023). In recent decades, there has been a pronounced increase in new housing development in the northern and southern parts of the city.

The 1/5000-scale Master Development Plan, approved in 2014 with a target year of 2045, sets out the principal planning decisions guiding Erzurum's spatial development (Figure 1b). Within this framework, housing development areas are primarily designated in the northwestern and southwestern parts of the city and extend toward the expressway. Urban regeneration areas are defined where newly designated development zones intersect with the existing urban

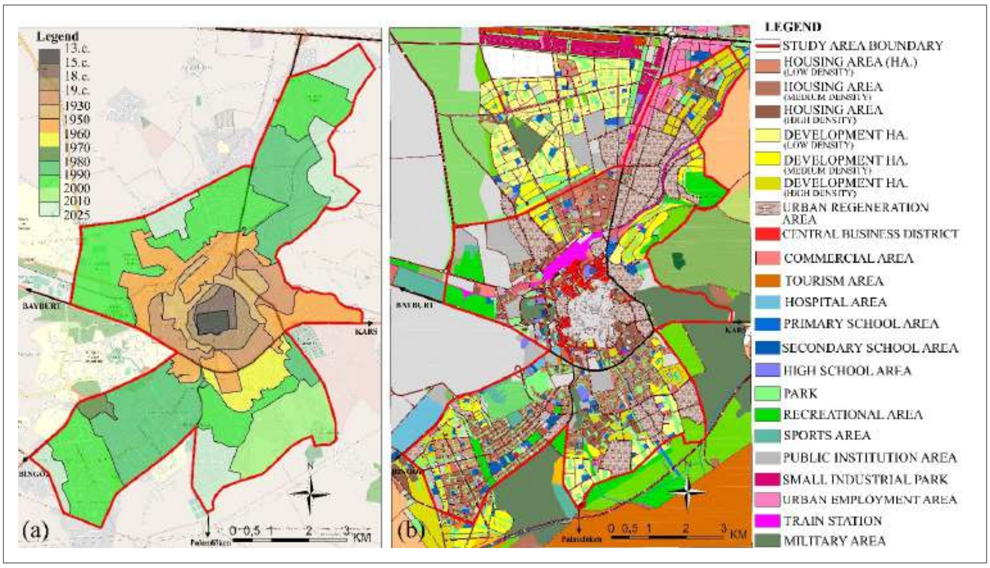

Figure 1. **(a)** The spatial development pattern of Erzurum, **(b)** 1/5000-scale Master Development Plan (Planevi Planning Office, 2014).

fabric, indicating that planning decisions directly shape the structure of housing supply and spatial density patterns. By contrast, housing areas expanding toward the urban periphery are generally planned at lower densities.

The southwestern development area began to develop after 1980, with the aim of providing an alternative to unplanned squatter settlements through cooperative housing projects that initially emphasized environmental balance (Terzi et al., 2025). However, the completion of the City Hospital investment in 2020 led to a rapid increase in housing demand in this area and generated strong pressure for intensive development. During this period, environmental considerations gradually weakened, and a tendency toward maximizing development density became evident. Accordingly, in the 2045 projection master plan, this area is defined as a high-density housing development area.

Another major development area is located in the northeastern part of the city, where neighborhoods largely built during the 1980s have been designated as urban regeneration areas. In this zone, new housing development areas extending toward the expressway have also been proposed. This planning approach reflects a strategy that simultaneously promotes urban regeneration of the existing building stock and the spatial expansion of the city. Overall, planning decisions in Erzurum have played a decisive role in determining the location, density, and environmental characteristics of housing development areas, contributing to the emergence of differentiated housing market dynamics across the urban space.

For the purposes of this study, a cross-sectional dataset was compiled using complementary online real estate data sources. Endeksa.com, one of Türkiye's most comprehensive real estate analytics platforms, was initially consulted to identify Erzurum as the province exhibiting the highest annual increase in housing prices in 2024, which motivated the selection of the study area. However, since Endeksa.com does not provide unit-level listing prices and detailed property attributes required for micro-scale spatial analysis, individual housing prices and property-specific characteristics were compiled from publicly available online real estate listings published on Sahibinden.com, one of the largest property advertisement platforms in Türkiye. The final dataset includes listing prices and property-specific characteristics for 1,596 apartments offered for sale in Erzurum during the June-July 2025 period. According to official statistics (TurkStat, 2025), housing market activity in Erzurum exhibits a concentration of both building permit issuance and transaction volumes during the summer months, which informed the selection of the study period. Moreover, the analysis adopts a narrow temporal window to ensure that observed price differences primarily reflect spatial and structural determinants rather than temporal variation.

To ensure data consistency and comparability, the analysis focused exclusively on residential properties categorized as apartments, excluding detached houses, duplexes, and basement units. The spatial distribution of the sampled properties in the study is illustrated in Figure 2. The spatial concentration of housing transactions exhibits a strong association with the city's urban development dynamics. The density map indicates a high concentration of transactions in areas surrounding the historical core of Erzurum and along its northwestern periphery. This pattern indicates that, despite the relatively older building stock in the central areas, regeneration pressures in adjacent neighborhoods and accessibility advantages continue to exert a significant

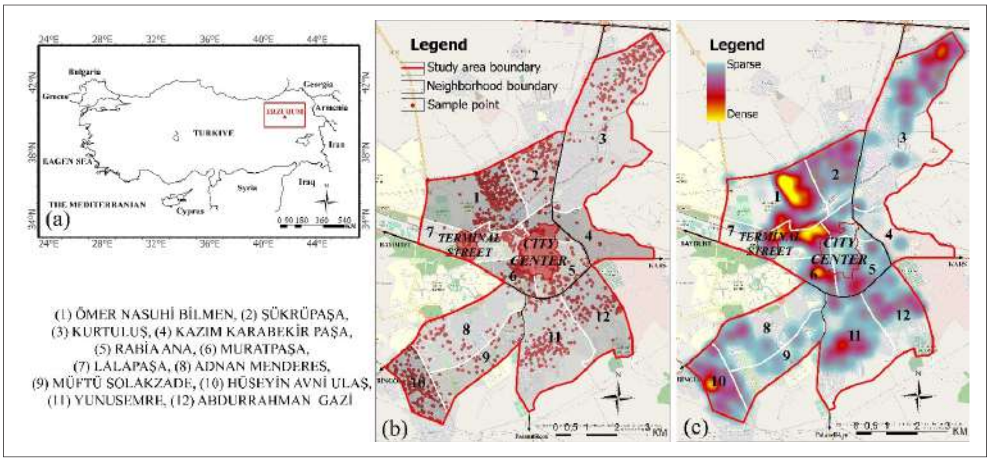

Figure 2.(a) The location of Erzurum, **(b)** Housing units' distribution, **(c)** Spatial heat map illustrating the concentration of housing units.

influence on housing market activity.

Furthermore, increasing concentrations of housing transactions are also observed in the northern and southern peripheral zones identified as development areas in the 1/5000-scale Master Development Plan. In particular, notable clusters of transactions emerge in the northwestern part of the city, especially within urban regeneration areas and around Terminal Street. These locations illustrate how new housing supply shaped by planning decisions, together with intensified commercial activity, generates spatially selective demand within the housing market.

The observed density pattern indicates that the housing market in Erzurum is not exclusively centered around the historical center. Instead, it displays a spatial configuration that evolves along planned development areas, regeneration zones, and major transportation corridors. This spatial pattern indicates a close relationship between housing market activity and urban planning decisions, thereby providing an essential contextual framework for interpreting the empirical findings of this study.

Explanatory Variables

To elucidate the determinants of housing prices, explanatory variables were systematically evaluated under two primary categories: Structural and environmental. The structural characteristics of a residence encompass its physical and equipment components, including the floor area (m^2), the number of rooms, the building age, the total number of floors, the floor level, the number of bathrooms, the heating type, the availability of covered parking, the location within a gated community, smart home features, elevator availability, and the presence of furnishings. These indicators, widely recognized in the literature as the fundamental parameters of hedonic price models, directly influence the market valuation of housing (Alkan Gökler, 2017; Kopczewska & Ćwiakowski, 2021; Sisman & Aydinoglu, 2022).

Environmental characteristics capture the locational and quality-of-life dimensions that shape housing values. Distance to the CBD (DCBD) was used to represent the monetary and temporal costs associated with access to the urban core (Alonso, 1964; Jin et al., 2022; Liu et al., 2024). In this study, the CBD was operationally defined as the historic and administrative core of Erzurum, where commercial activities and public services are most concentrated. Accordingly, the DCBD was calculated as the Euclidean distance from each housing unit to the CBD using the Near Distance tool in ArcGIS Pro.

Green area density was assessed via the NDVI, derived from Landsat 8/9 OLI satellite imagery. While many previous studies have defined green space indicators through official land-use classifications or planning inventories, this study directly measured vegetation density surrounding dwellings. In doing so, both the spatial concentration and ecological quality of greenery were incorporated into the model in an objective and fine-grained manner (Du et al., 2018; Samad et al., 2020).

Accessibility metrics were derived from connectivity, betweenness, and closeness indices, which capture the degree of spatial integration within the street network. As evidenced by Space Syntax and sDNA-based studies, these measures reflect not only spatial distance but also the positional importance of each housing within the urban network (Law et al., 2017; Abdulla & Ibrahim, 2023; Liu et al., 2024). In this study, the betweenness (TPBtA) and closeness (MAD) indices were calculated using the sDNA method with street network data obtained from Open Street Maps, using the widely accepted 800-meter walking distance threshold. This threshold is a commonly applied scale for pedestrian-level accessibility analyses (Li et al., 2023; Khosravi et al., 2024). To operationalize these indicators at the housing scale, network-based buffer zones with a 100-meter radius were defined around each property, and the average index values within these buffers were assigned to the respective dwellings (Pozo et al., 2025). This approach preserved the theoretical 800 m pedestrian scale while generating housing-specific accessibility measures. The network-based buffer technique has been shown to offer a more realistic representation of spatial conditions than circular buffers, as it directly incorporates street network configurations (Güller, 2025).

In total, 17 candidate variables were initially considered (Table 2). Following statistical significance and multicollinearity diagnostics, nine variables were retained in the final model: Floor area, building age, number of floors, floor level, heating type, distance to the city center (DCBD), NDVI, connectivity, and TPBtA800. Multicollinearity was assessed using the Variance Inflation Factor (VIF) test, and variables with VIF values exceeding 7.5 were excluded (Wang et al., 2020). The retained variables yielded VIF scores between 1.04 and 1.96, indicating the robustness and reliability of the final model.

Geographically Weighted Regression

The empirical analysis began with an optimized hotspot analysis, a spatial statistical technique designed to detect and visualize clustering patterns in housing prices (Figure 3). This procedure integrates both Global Moran's I and Getis-Ord Gi* statistics, enabling the identification of statistically significant concentrations of high and low values within the study area (Kortas et al., 2022; Hsieh & Yang, 2024). The Optimized Hotspot Analysis tool in ArcGIS Pro automatically determines the most appropriate distance band for the dataset, thereby minimizing the subjectivity associated with traditional hotspot methods (Esri, 2025).

Following this exploratory stage, GWR was employed to model the spatially heterogeneous relationships between structural and environmental variables and housing prices. Unlike conventional global regression models, which assume constant relationships across areas, GWR estimates location-specific coefficients, thus capturing the local variations that characterize housing market dynamics (Sisman & Aydinoglu, 2022).

A critical step in GWR calibration involves the selection of bandwidth. According to Bujanda & Fullerton (2017), the use of adaptive kernel bandwidths is preferable when ob-

Table 2. Summary of variables

Category	Variable	Variable definition and measurement method
Dependent Variable	**PRICE**	**Total housing price**
Structural variables	FLOOR AREA	Total usage area of the housing in the m^2 unit
	NOROOM	Total number of rooms in the housing
	AGE	Time (year) from the date of construction of the apartment to the present day
	NOFLOOR	The total number of floors in the apartment
	FLOOR LEVEL	The floor level of the housing in the apartment
	NOBATHROOM	Total number of bathrooms in the housing
	HEATING TYPE	Stove–1, combi boiler–2, central heating–3, underfloor heating–4
	COVERED PARKING	Whether the apartment has a covered parking variable or not (available-1, not available-0)
	GATED COMMUNITY	Whether the apartment is in a gated community or not (within the gated community-1, others-0)
	SMART HOME	Whether the apartment is a smart home or not (smart home -1, others-0)
	ELEVATOR	Whether the apartment has an elevator variable (available-1, not available-0)
	FURNISHED	Whether the housing is furnished (furnished–1, unfurnished–0)
Environmental variables	DCBD	Distance to CBD (km)
	NDVI	Vegetation density index around housing
	CONNECTIVITY	Number of direct street links
	TPBtA	Betweenness index derived from sDNA, measuring how often a street lies on shortest paths
	MAD	Closeness index derived from sDNA, measuring average angular distance to all other nodes

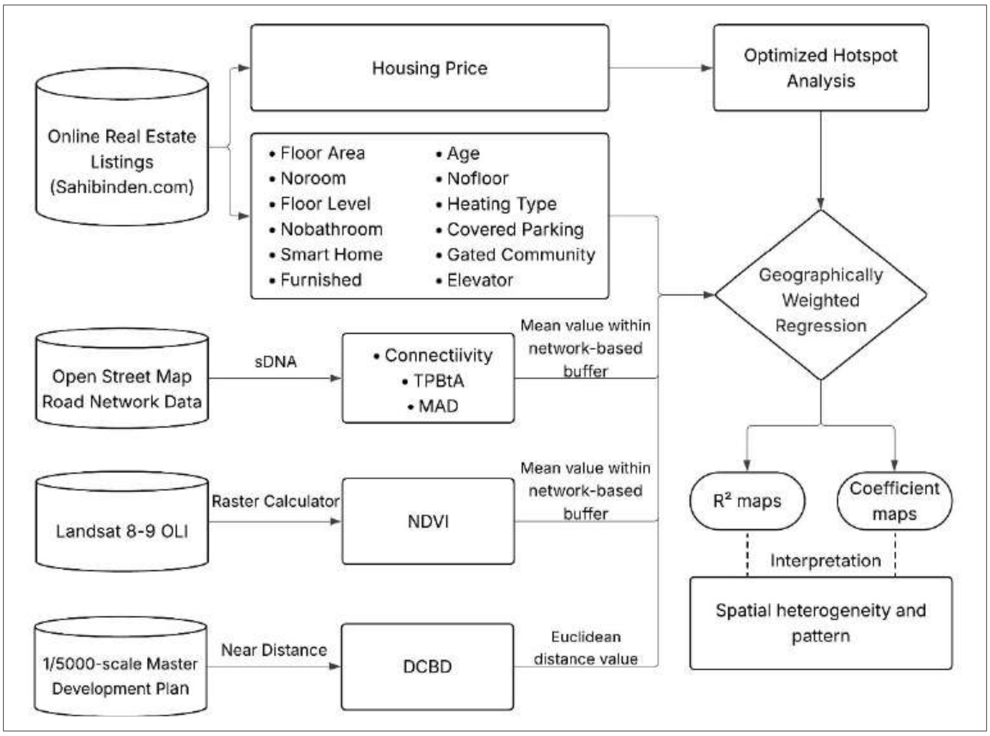

Figure 3. The method and procedure schema of the study.

servations are unevenly distributed, as it ensures that a fixed number of neighbors is considered for each location. This approach mitigates the biases that may arise from irregular densities. In contrast, fixed kernels apply the same spatial radius everywhere, which can distort results in contexts with clustered or sparse data (Moralı & Yılmaz, 2020; Güneş & Apaydın, 2022). In this study, an adaptive bandwidth with a Gaussian kernel weighting function was implemented. Bandwidth optimization was performed using the golden section search algorithm available in ArcGIS Pro, and the model specification with the lowest Akaike Information Criterion (AIC) value was selected for final analysis.

RESULTS AND DISCUSSION

Evolution of the Spatial Pattern of House Prices

The results revealed that residential property prices in Erzurum exhibited significant positive spatial autocorrelation, forming both high-high and low-low clusters (Figure 4). The southeastern part of the city was dominated by low-low clusters, whereas high-high clusters were concentrated in the northwestern and southwestern districts, corresponding to newly developed residential zones. Interestingly, the emergence of low-low clusters in certain northern districts—also classified as new development areas—highlighted the pronounced spatial heterogeneity in price formation.

In contrast, the central districts were largely characterized by low-low clusters or statistically significant but less coherent spatial groupings. This pattern diverges from the prevailing tendency reported in the literature, which typically suggests a gradual decline in housing prices from the city center to the periphery (Kopczewska & Ćwiakowski, 2021; Wang et al., 2022b). Numerous studies indicate that high-price clusters tend to concentrate in urban cores, while low-price clusters are more frequently located in peripheral zones (Cui et al., 2018; Li et al., 2019; Zhang et al., 2019a).

However, these assumptions were insufficient to explain the Erzurum case. The findings suggest that the relatively aged and low-quality building stock in the city center, coupled with the shift in housing demand toward western development areas, has hindered the formation of high-price clusters in the core. Instead, new growth zones in the periphery have emerged as the focal point of price premiums. This dynamic indicates that Erzurum's spatial development dynamics differentiate the center-periphery relationship in the housing market. These findings provide an important contextual foundation for the first research question by demonstrating that housing price formation in Erzurum is inherently spatially heterogeneous and cannot be adequately explained by uniform center-periphery assumptions.

GWR Model Estimation and Fit Performance

The GWR model achieved strong explanatory performance, with an R^2 of 0.867 and an adjusted R^2 of 0.834, while the AICc value of 3661.98 confirmed the superiority of the local specification over global alternatives. Residual diagnostics further supported the robustness of the model: Standardized residuals followed an approximately normal

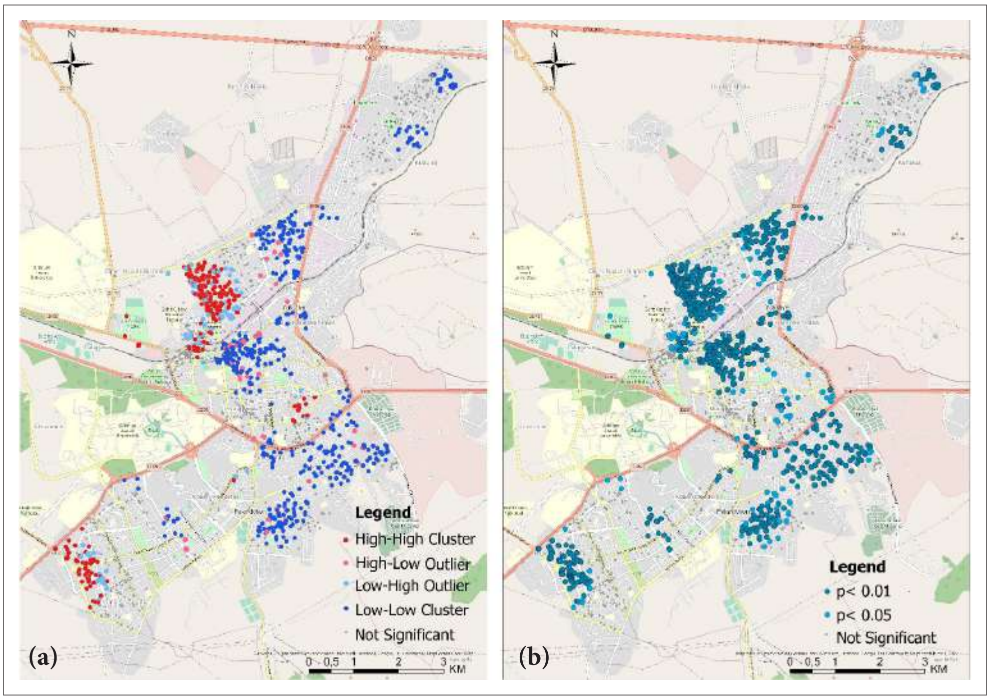

Figure 4. **(a)** Optimized outlier analysis and **(b)** p-values.

distribution, with most values within ±2 standard deviations and only minor deviations at the tails, while the QQ plot showed close alignment with the theoretical normal line (Figure 5). Importantly, the Global Moran's I test of standardized residuals produced a non-significant result (I=-0.009, z=-0.549, p=0.583). Moran's I measures whether model errors exhibit spatial clustering; a significant positive value would indicate that errors are spatially correlated and that the model failed to capture important spatial processes (Du et al., 2018; Güneş & Apaydın, 2022). In this study, the near-zero and insignificant Moran's I demonstrates that the residuals were randomly distributed across space, meaning that the GWR model had successfully captured the spatial dependence in housing prices and eliminated serious spatial autocorrelation in the errors. By effectively accounting for spatial dependence, the GWR framework provides strong evidence of the model's validity and reliability for addressing both research questions, particularly those concerning spatially varying effects.

The GWR model, by explicitly accounting for spatial heterogeneity, exhibited marked variation in its local explanatory capacity across the study area. The distribution of local R^2 values indicated that the model's explanatory power was not spatially uniform: Most observations exhibited a value between 0.70 and 0.90, with a mean of 0.76. This highlights areas where the model performs particularly well, as well as areas where unobserved local factors may weaken its explanatory strength. The GWR model recorded its highest explanatory values in the southwestern districts and the lowest in the northeast, while its per-

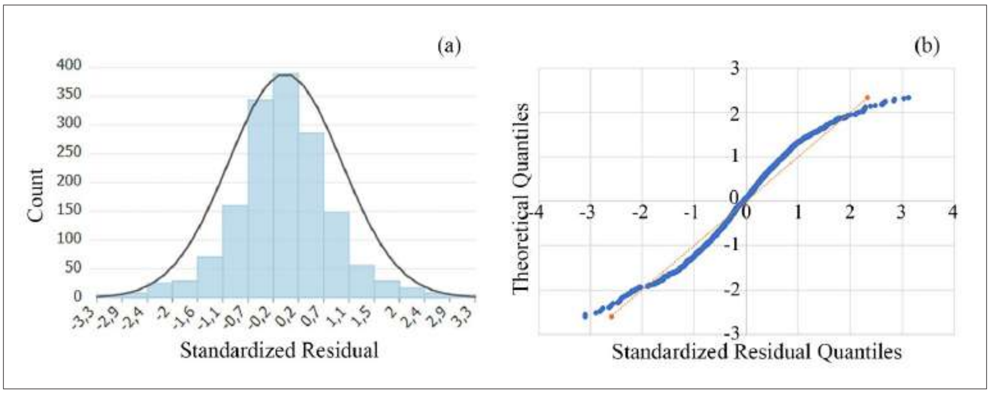

Figure 5. Residual diagnostics for the GWR model: **(a)** Histogram of standardized residuals with normal curve; **(b)** Normal QQ plot of standardized residuals against theoretical quantiles.

Megaron, Vol. 21, No. 1, pp. 42–61, March 2026

formance in the central and eastern parts of the city was relatively consistent (Figure 6).

Geographical Distribution of GWR Coefficient Estimates

The spatial distribution of GWR local parameters was examined by mapping only statistically significant results. The findings indicated that the model's local coefficients varied across locations, demonstrating that the determinants of housing prices were heterogeneous in space (Figure 7a). In direct response to the first research question, these results confirm that the effects of structural and environmental characteristics are not spatially uniform but vary considerably across the urban fabric.

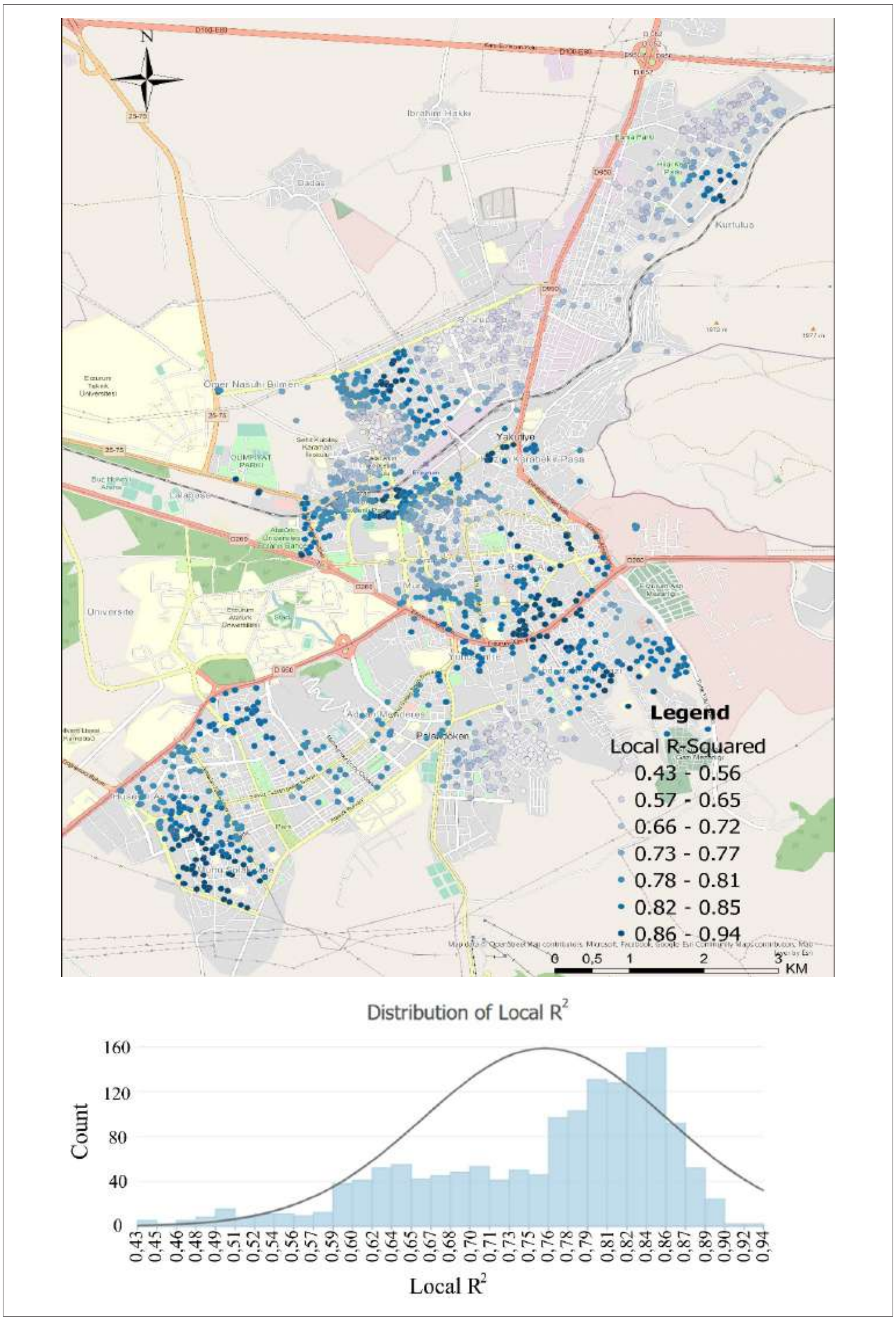

Figure 6. Geographical distribution of local R² values of the GWR model in the study area.

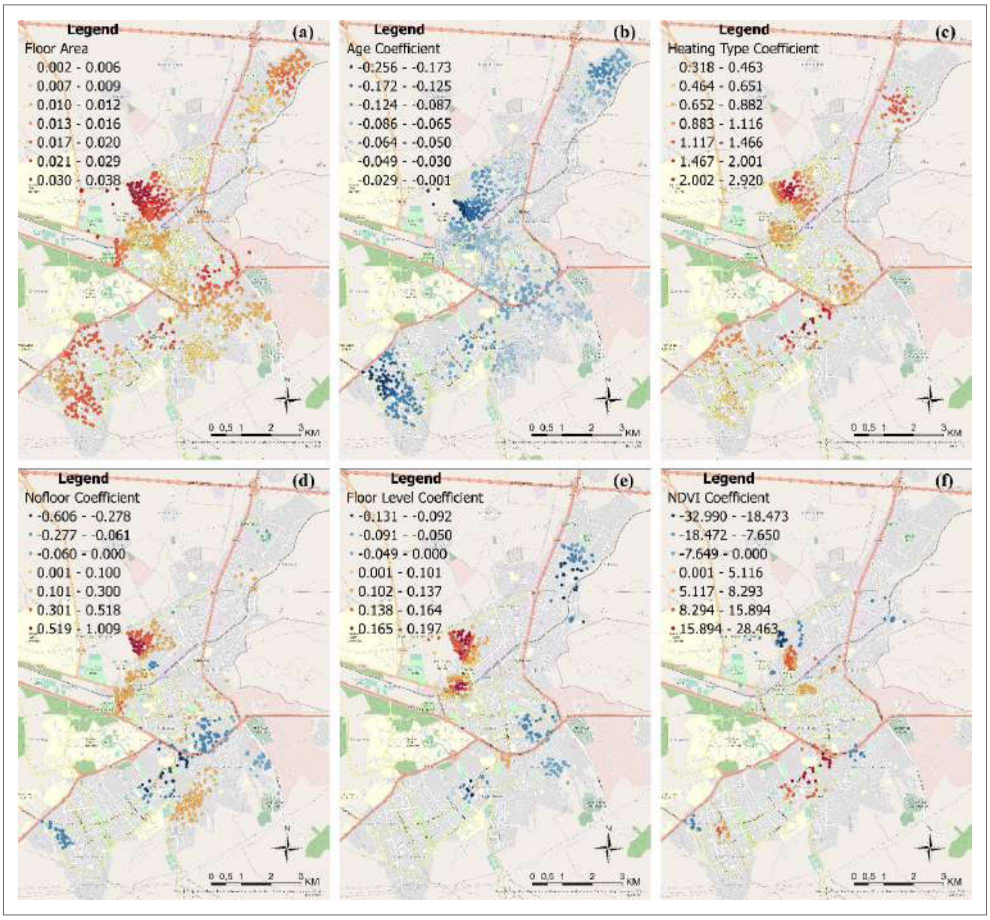

Figure 7. GWR model coefficients of **(a)** floor area; **(b)** age; **(c)** heating type; **(d)** Nofloor; **(e)** floor level; **(f)** NDVI.

Specifically, floor area (m²) and building age emerged as the most consistent predictors of housing values, both of which were found to be statistically significant in a large portion of the study area. This finding is consistent with the extant literature, which demonstrates a positive correlation between unit size and housing price (Moralı & Yılmaz, 2020; Sisman & Aydinoglu, 2022). A further examination revealed that floor area attained its highest coefficient values in the northwestern development zones. This phenomenon can be attributed to the diversity introduced by varying unit sizes (Zahirovich-Herbert & Gibler, 2014), which highlights how product heterogeneity increases price differentials and strengthens the role of square footage as a determinant of value.

The building age variable exhibited a negative correlation with prices, as expected (Figure 7b). This result may be explained by buyers' preference for newer buildings (Sisman & Aydinoglu, 2022; Wang et al., 2022a) and the advantages of reduced maintenance and improved equipment, particularly under Erzurum's severe winter conditions (Tian et al., 2017). The effect of building age was most pronounced in high-density development zones in the southwest and northwest, while its impact was weakest in the CBD and the Terminal Street corridor, where commercial activity is particularly dense. In line with prior research, the mitigating influence of centrality indicates that the locational advantages of core districts offset the depreciation effect of older building stock (Tomal, 2020; Güneş & Apaydın, 2022). This pattern underscores the notion that the role of building age in shaping housing values is highly context-dependent. In areas proximate to urban centers, the location advantage mitigates the value loss associated with older buildings.

Heating type had a stronger influence on housing prices than both floor area and building age (Figure 7c). Local coefficients increased from individual systems to central heating, indicating that centrally heated buildings commanded higher values. This finding aligns with literature emphasizing that central systems enhance real estate value by improving energy efficiency, reducing costs, and lowering emissions (Noh et al., 2025). Given Erzurum's harsh climate, this result is unsurprising, yet the spatial distribution revealed variability: The strongest coefficients were recorded in northwestern development areas, while the effect in Yıldızkent was relatively weak. This suggests that

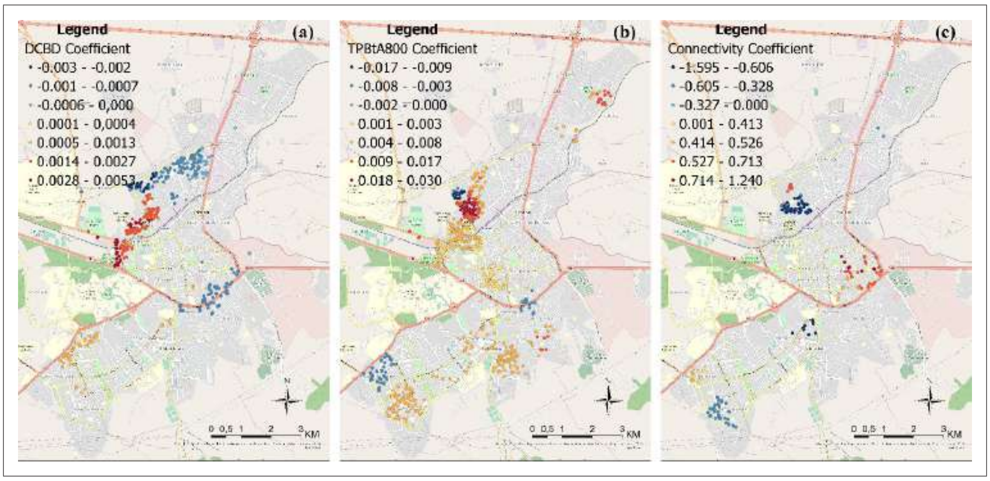

Figure 8. GWR model coefficients of **(a)** DCBD; **(b)** TPBtA800; **(c)** connectivity.

widespread adoption of central heating reduces local differentiation. Overall, heating infrastructure emerges as not merely a technical provision but also a strategic determinant of market value.

The nofloor variable exhibited a price-increasing role in the majority of the city (Figure 7d). In new development zones and commercial areas such as Terminal Street, additional floors significantly raised housing values. This finding is consistent with previous studies suggesting that nofloor exerts a positive influence in dense and centrally located neighborhoods (Sisman & Aydinoglu, 2022). Similarly, in Kayakyolu, located in the south, multi-story buildings contributed to higher values due to modern construction techniques, amenities such as elevators and parking, and the Palandöken views advantage. Conversely, in older neighborhoods, an increase in nofloor was associated with lower prices, particularly in Yenişehir and the eastern periphery. Here, multi-story stock appeared to be less desirable, likely due to structural deterioration and seismic risk concerns (Yiu & Cheung, 2022; Shi & Naylor, 2023). These patterns demonstrate that nofloor can be value-enhancing or value-reducing depending on neighborhood conditions.

The floor level variable demonstrated positive effects in new development areas but weaker or negative impacts in older districts (Figure 7e). Unlike earlier studies that generally reported uniformly positive effects (Li et al., 2019; Sisman & Aydinoglu, 2022), the present analysis indicated that higher floors reduced values in older neighborhoods. Poor insulation in upper floors of aged buildings under harsh winters appeared to drive this trend. Conversely, in new housing zones on the plain, upper floors became more desirable due to better air quality, views, and reduced noise (Saphores & Aguilar-Benitez, 2005; Lin et al., 2014; Cellmer et al., 2020). Even in areas with older stock near Buhara Hospital, upper floors were associated with a higher value, likely due to traffic and pollution lowering the attractiveness of ground-level units (Lu et al., 2023). These findings highlight that floor level effects are mediated by both structural conditions and environmental quality.

NDVI generally emerged as a value-enhancing factor (Figure 7f). Greenery improves quality of life by mitigating noise and air pollution, thereby supporting housing values (Tian et al., 2017; Kopczewska & Ćwiakowski, 2021). The willingness of Erzurum residents to pay more for green amenities is consistent with prior findings (Du et al., 2018; Liebelt et al., 2019; Wu et al., 2019; Kim & Kim, 2020). Yet, in some peripheral development areas, higher NDVI was paradoxically linked to lower prices. This outcome reflects that the quantity and quality of vegetation matter: Agricultural plots, vacant land, and immature landscaping did not contribute to higher values. Thus, the decisive element in housing markets is not mere vegetation density but the availability of accessible, functional, and high-quality green spaces.

The findings indicated that DCBD coefficients were negative in the southern periphery of the city center and in the northern part of the city, confirming that prices decreased with distance (Figure 8a). This finding aligns with prior studies showing that residential proximity to commercial centers supports higher values (Du et al., 2018; Wu et al., 2019). However, this relationship weakened in new commercial hubs such as Yıldızkent and Terminal Street. The findings of the study indicate that local commercial sub-centers can offset distance to the historic core (Zhang et al., 2019a) and that buyers consider not only traditional centers but also commercial opportunities within their living environments.

With respect to the second research question, the spatial distribution of sDNA-based accessibility indicators reveals that street network characteristics play a context-sensitive role in shaping the spatial pattern of housing prices. The TPBtA800 index, representing pedestrian accessibility, generally emerged as a value-enhancing factor, though with spatial variations (Figure 8b). The findings indicated that local coefficients were elevated in new development areas, while their effect remained comparatively constrained in the city center. This indicates that pedestrian-oriented accessibility contributes more strongly to price formation in areas where network maturity is still evolving (Tian et al., 2017). In contrast, it is noteworthy that the TPBtA800 index had a price-reducing effect on main boulevards. The observed outcomes can be attributed to a number of factors, including high traffic volumes, pedestrian-unfriendly street layouts, and environmental disadvantages in the area surrounding main boulevards. This suggests that buyers in these areas have a preference for human-scale environments and are willing to pay more for such conditions (Özüduru & Yücesoy, 2018; Liu et al., 2025). Moreover, the coexistence of high-rise density in these corridors further reinforced negative pricing effects, highlighting the market drawbacks of density-oriented regulations. Therefore, it is concluded that while the betweenness index is critical in explaining housing values, it should be supported by pedestrian-focused interventions.

Finally, the connectivity coefficients revealed that, in contrast to the betweenness index, higher connectivity along major streets increased prices (Figure 8c). These results demonstrate that sDNA-derived accessibility metrics contribute to explaining the spatial configuration of housing prices beyond traditional distance-based measures, thereby directly addressing the second research question. Moreover, the findings indicate that local access opportunities are more influential for housing markets than global centrality measures (Law et al., 2017; Yang et al., 2018; Abdulla & Ibrahim, 2023). In mature network contexts, connectivity enhanced accessibility advantages and market appeal. By contrast, in new development zones, higher connectivity failed to improve prices, largely because links often terminated in dead ends within an incomplete network structure. Thus, immature street networks produced fragmentation rather than functional benefits. This underscores that the relationship between local access and global centrality is highly context-sensitive, and spatial morphology can exert divergent effects depending on the developmental stage of the urban fabric.

CONCLUSION

This study reveals the spatial heterogeneity of structural and environmental determinants of housing prices, demonstrating that real estate markets are shaped not only by supply-demand dynamics but also by urban form, environmental quality, and infrastructure. The findings highlight the qualities households prioritize in their housing preferences, thereby offering concrete guidance for urban planning and housing policy design.

By employing network-based accessibility metrics, this research departed from conventional approaches that rely primarily on distance-based measures. The results indicate that street networks function not merely as transport corridors but as integral components of urban infrastructure that influence housing market dynamics. In particular, spatial network indicators such as connectivity and betweenness illustrate how local access and global centrality differentially affect prices. Consistent with previous studies, higher levels of connectivity are associated with increased housing values in mature urban networks (Tian et al., 2017; Abdulla & Ibrahim, 2023). However, the findings further demonstrate that the effect of betweenness is highly context-dependent. In line with Liu et al. (2024) and Chakrabarti et al. (2022), pedestrian-oriented betweenness in newly developing areas is more likely to support housing price premiums, whereas increased betweenness along traffic-dominated corridors tends to generate negative externalities. These results emphasize that accessibility indicators are not inherently value-enhancing; rather, their effects depend on network configuration, environmental conditions, and broader urban form.

Beyond accessibility, this study provides key insights into the complex interplay between structural and environmental variables in shaping housing markets, generating several planning-oriented implications.

1. Contrary to typical expectations in the housing market (Cui et al., 2018; Li et al., 2019; Wang et al., 2025), the relocation of high-priced housing clusters toward the northwestern and southwestern peripheries of Erzurum reflects a shift in planning-driven housing attractiveness. When combined with the relative inadequacy of the aging central housing stock, this trend underscores the need for integrated planning strategies that simultaneously promote central area regeneration and carefully manage peripheral expansion. Achieving this balance is essential for achieving equitable and sustainable urban development.

2. The strong and spatially differentiated influence of heating systems highlights the critical role of energy infrastructure in housing markets, particularly in cold-climate cities. In line with Noh et al. (2025) and Ben et al. (2023), centralized heating systems are found to significantly increase housing values, suggesting that energy-efficient infrastructure should be treated as a core element of housing policy rather than a secondary technical consideration. Moreover, the locally varying effects of building height and floor level (Chau et al., 2001; Xiao et al., 2019) indicate that density regulations should be context-sensitive. It demonstrates the need to avoid uniform standards that do not take into account environmental conditions, building quality, and neighborhood characteristics.

3. The spatially heterogeneous effect of NDVI confirms the notion that environmental quality, rather than the mere presence of green space, exerts a pivotal influence on housing price formation. Consistent with Kim & Kim (2020) and Soltani et al. (2026), accessible, well-integrated, and function-

al green areas are associated with positive price premiums, whereas undeveloped or poorly integrated vegetation tends to exert weaker or even negative effects. This result highlights the importance of moving beyond quantitative green space targets toward qualitative planning approaches that emphasize accessibility, usability, and ecological integration.

Methodologically, the use of GWR allowed the study to effectively capture local-level price determinants while addressing both spatial heterogeneity and autocorrelation. Nevertheless, several limitations should be acknowledged. First, the analysis relied on cross-sectional data, and future research incorporating longitudinal datasets could provide insights into temporal dynamics. Second, a uniform bandwidth was applied across variables; adopting multiscale GWR would enable more nuanced detection of variable-specific effects. Finally, incorporating finer-grained classifications of social infrastructure variables, such as education and health facilities, may enhance explanatory power.

In conclusion, this study demonstrates the multidimensional link between urban planning and real estate markets and offers two key messages for planners: (i) Spatial context fundamentally alters the effect of the same variable on market outcomes; and (ii) structural investments should be coupled with environmental quality to foster sustainable and balanced growth in housing markets.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Abdulla, H. M., & Ibrahim, M. A. (2023). The impact of urban spatial plan on land value: An approach system to relating space syntax premises to the land price. *Sustainability, 15*(9), 7239. https://doi.org/10.3390/su15097239

Abdulla, H. M., Ibrahim, M. A., & Al-Hinkawi, W. S. (2023). The impact of urban street network on land value: Correlate syntactical premises to the land price. *Buildings, 13*(7), 1610. https://doi.org/10.3390/buildings13071610

Aboelata, A., & Sodoudi, S. (2019). Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo. *Building and Environment, 166*, 106407. https://doi.org/10.1016/j.buildenv.2019.106407

Adair, A. S., Berry, J. N., & McGreal, W. S. (1996). Hedonic modelling, housing submarkets and residential valuation. *Journal of Property Research, 13*(1), 67–83. https://doi.org/10.1080/095999196368899

Adetunji, A. B., Akande, O. N., Ajala, F. A., Oyewo, O., Akande, Y. F., & Oluwadara, G. (2022). House price prediction using random forest machine learning technique. *Procedia Computer Science, 199*, 806–813. https://doi.org/10.1016/j.procs.2022.01.100

Alkan Gökler, L. (2017). Examining house price differentiation in Ankara using hedonic analysis. *Megaron, 12*(2), 304–315. https://doi.org/10.5505/megaron.2017.35582

Alonso, W. (1964). *Location and land use: Toward a general theory of land rent*. Harvard University Press. https://doi.org/10.4159/harvard.9780674730854

Barnes, C., Knio, R., & Sakoglu, U. (2025). Home price prediction using enhanced features from the environment. *Procedia Computer Science, 258*, 2837–2845. https://doi.org/10.1016/j.procs.2025.04.544

Belcher, R. N., & Chisholm, R. A. (2018). Tropical vegetation and residential property value: A hedonic pricing analysis in Singapore. *Ecological Economics, 149*, 149–159. https://doi.org/10.1016/j.ecolecon.2018.03.012

Ben, S., Zhu, H., Lu, J., & Wang, R. (2023). Valuing the accessibility of green spaces in the housing market: A spatial hedonic analysis in Shanghai, China. *Land, 12*(9), 1660. https://doi.org/10.3390/land12091660

Bovkir, R., & Aydinoglu, A. C. (2018). Providing land value information from geographic data infrastructure by using fuzzy logic analysis approach. *Land Use Policy, 78*, 46–60. https://doi.org/10.1016/j.landusepol.2018.06.040

Brown, J. N., & Rosen, H. S. (1982). On the estimation of structural hedonic price models. *Econometrica, 50*(3), 765–768. https://doi.org/10.2307/1912614

Bujanda, A., & Fullerton, T. M. (2017). Impacts of transportation infrastructure on single-family property values. *Applied Economics, 49*(51), 5183–5199. https://doi.org/10.1080/00036846.2017.1302064

Can, A. (1990). The measurement of neighborhood dynamics in urban house prices. *Economic Geography, 66*(3), 254–272. https://doi.org/10.2307/143400

Çamur, K., Dursun, D., & Kaya, A. B. (2023). Agricultural land change, planning and urbanisation: A case study from Erzurum, Türkiye (1940–2022). *Planning Perspectives, 38*(6), 1233–1255. https://doi.org/10.1080/02665433.2023.2187440

Cellmer, R., Cichulska, A., & Bełej, M. (2020). Spatial analysis of housing prices and market activity with the geographically weighted regression. *ISPRS International Journal of Geo-Information, 9*(6), 380. https://doi.org/10.3390/ijgi9060380

Chakrabarti, S., Kushari, T., & Mazumder, T. (2022). Does transportation network centrality determine housing price? *Journal of Transport Geography, 103*, 103397. https://doi.org/10.1016/j.jtrangeo.2022.103397

Chau, K. W., Wong, S. K., Yau, Y., & Yeung, A. K. C. (2007). Determining optimal building height. *Urban Studies, 44*(3), 591–607. https://doi.org/10.1080/00420980601131902

Chau, K., Ma, V., & Ho, D. (2001). The pricing of 'luckiness' in the apartment market. *Journal of Real Estate Literature, 9*(1), 29–40. https://doi.org/10.1080/10835547.2001.12090095

Chen, J. H., Ong, C. F., Zheng, L., & Hsu, S. C. (2017). Forecasting spatial dynamics of the housing market using support vector machine. *International Journal of Strategic Property Management, 21*(3), 273–283. https://doi.org/10.3846/1648715X.2016.1259190

Chen, W. Y., & Jim, C. Y. (2010). Amenities and disamenities: A hedonic analysis of the heterogeneous urban landscape in Shenzhen (China). *Geographical Journal, 176*(3), 227–240. https://doi.org/10.1111/j.1475-4959.2010.00358.x

Cho, S. H., Clark, C. D., Park, W. M., & Kim, S. G. (2009). Spatial and temporal variation in the housing market values of lot size and open space. *Land Economics, 85*(1), 51–73. https://doi.org/10.3368/le.85.1.51

Comber, A., Brunsdon, C., Charlton, M., Dong, G., Harris, R., Lu, B., Lü, Y., Murakami, D., Nakaya, T., Wang, Y., & Harris, P. (2023). A route map for successful applications of geographically weighted regression. *Geographical Analysis, 55*(1), 155–178. https://doi.org/10.1111/gean.12316

Cui, N., Gu, H., Shen, T., & Feng, C. (2018). The impact of micro-level influencing factors on home value: A housing price-rent comparison. *Sustainability, 10*(12), 4343. https://doi.org/10.3390/su10124343

De Araujo, P., & Cheng, K. (2017). Do preferences for amenities differ among home buyers? A hedonic price approach. *Review of Urban & Regional Development Studies, 29*(3), 165–184. https://doi.org/10.1111/rurd.12061

De Palma, A., Motamedi, K., Picard, N., & Waddel, P. (2005). A model of residential location choice with endogenous housing prices and traffic for the Paris region. *International Journal of Transport Economics, Engineering and Law, 11*(31), 67–82.

Dimopoulos, T., Tyralis, H., Bakas, N. P., & Hadjimitsis, D. (2018). Accuracy measurement of random forests and linear regression for mass appraisal models that estimate the prices of residential apartments in Nicosia, Cyprus. *Advances in Geosciences, 45*, 377–382. https://doi.org/10.5194/adgeo-45-377-2018

Ding, J., Cen, W., Wu, S., Chen, Y., Qi, J., Huang, B., & Du, Z. (2024). A neural network model to optimize the measure of spatial proximity in geographically weighted regression approach: A case study on house price in Wuhan. *International Journal of Geographical Information Science, 38*(7), 1315–1335. https://doi.org/10.1080/13658816.2024.2343771

Du, Q., Wu, C., Ye, X., Ren, F., & Lin, Y. (2018). Evaluating the effects of landscape on housing prices in urban China. *Tijdschrift voor Economische en Sociale Geografie, 109*(4), 525–541. https://doi.org/10.1111/tesg.12308

Ebru, Ç., & Eban, A. (2011). Determinants of house prices in Istanbul: A quantile regression approach. *Quality & Quantity, 45*(2), 305–317. https://doi.org/10.1007/s11135-009-9296-x

Ekşioğlu Çetintahra, G., & Çubukçu, E. (2011). The effect of environmental aesthetics on house prices. *İTÜDERGİSİ/a, 10*(1), 3–12.

Endeksa. (2025). *Endeksa*. Retrieved September 19, 2020, from https://www.endeksa.com/tr/

Esri. (2025). *Optimized hot spot analysis*. Retrieved August 1, 2020, from https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-statistics-toolbox/optimized-hot-spot-analysis.htm

Franco, S. F., & Macdonald, J. L. (2018). Measurement and valuation of urban greenness: Remote sensing and hedonic applications to Lisbon, Portugal. *Regional Science and Urban Economics, 72*, 156–180. https://doi.org/10.1016/j.regsciurbeco.2017.03.002

Gan, L., Ren, H., Xiang, W., Wu, K., & Cai, W. (2021). Nonlinear influence of public services on urban housing prices: A case study of China. *Land, 10*(10), 1007. https://doi.org/10.3390/land10101007

Genc, N., & Colak, H. E. (2025). Identifying influencers of housing prices: Spatial heterogeneity and pattern analysis using machine learning, spatial regression, and GIS. *Journal of Housing and the Built Environment*, 2025, 1–43. https://doi.org/10.1007/s10901-025-10244-8

Ghamrawi, T., & Nat, M. (2024). House value estimation using different regression machine learning techniques. *Acta Infologica, 8*(2), 245–259. https://doi.org/10.26650/acin.1543650

Goodman, A. C. (1978). Hedonic prices, price indices and housing markets. *Journal of Urban Economics, 5*(4), 471–484. https://doi.org/10.1016/0094-1190(78)90004-9

Gu, J., Wang, X., & Liu, G. (2021). Rediscovering the amenity value of urban landscapes in the mountainous areas with high-rise buildings from the perspective of 3D vertical urban systems. *Urban Forestry & Urban Greening, 60*, 127018. https://doi.org/10.1016/j.ufug.2021.127018

Güller, C. (2025). Investigating the relationship between built environment and spatiotemporal heterogeneity of metro ridership. *Travel Behaviour and Society, 40*, 101053. https://doi.org/10.1016/j.tbs.2025.101053

Güneş, T., & Apaydın, A. (2022). Spatial heterogeneity in housing market: Ankara metropolitan area. *Erciyes University Journal of Faculty of Economics and Administrative Sciences*, *63*, 9–15.s https://doi.org/10.18070/erciyesiibd.1122568

Haaland, C., & van Den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening, 14*(4), 760–771. https://doi.org/10.1016/j.ufug.2015.07.009

Ho, W. K., Tang, B. S., & Wong, S. W. (2021). Predicting property prices with machine learning algorithms. *Journal of Property Research, 38*(1), 48–70. https://doi.org/10.1080/09599916.2020.1832558

Hsieh, B. M., & Yang, C. Y. (2024). The effects of transaction hotspots and flipping hotspots on housing prices. *International Journal of Strategic Property Management, 28*(1), 1–15. https://doi.org/10.3846/ijspm.2024.20899

Hu, L., He, S., Han, Z., Xiao, H., Su, S., Weng, M., & Cai, Z. (2019). Monitoring housing rental prices based on social media: An integrated approach of machine-learning algorithms and hedonic modeling to inform equitable housing policies. *Land Use Policy, 82*, 657–673. https://doi.org/10.1016/j.landusepol.2018.12.030

Huang, J., Wang, Y., Wu, K., Yue, X., & Zhang, H. O. (2024). Livability-oriented urban built environment: What kind of built environment can increase the housing prices? *Journal of Urban Management, 13*(3), 357–371. https://doi.org/10.1016/j.jum.2024.04.001

Hui, E. C., Chau, C. K., Pun, L., & Law, M. Y. (2007). Measuring the neighboring and environmental effects on residential property value: Using spatial weighting matrix. *Building and Environment, 42*(6), 2333–2343. https://doi.org/10.1016/j.buildenv.2006.05.004

Jin, T., Cheng, L., Liu, Z., Cao, J., Huang, H., & Witlox, F. (2022). Nonlinear public transit accessibility effects on housing prices: Heterogeneity across price segments. *Transport Policy, 117*, 48–59. https://doi.org/10.1016/j.tranpol.2022.01.004

Kang, C. D. (2019). Effects of spatial access to neighborhood land-use density on housing prices: Evidence from a multilevel hedonic analysis in Seoul, South Korea. *Environment and Planning B: Urban Analytics and City Science, 46*(4), 603–625. https://doi.org/10.1177/2399808317721184

Kangallı-Uyar, S. G., & Keten, N. D. (2020). Modelling of housing prices by spatial quantile regression approach: A case of Denizli Province. *Business and Economics Research Journal, 11*(3), 713–734. https://doi.org/10.20409/berj.2020.270

Kangallı-Uyar, S. G., & Yayla, N. (2016). The estimation of housing prices within the frame of hedonic pricing approach by spatial econometric models: The case of İstanbul housing market. *Social Sciences, 11*(4), 326–342.

Khosravi, H., Abrishami, M., Mehrian, M. R., & Chamberlain, B. (2024). The positive impact of transit-oriented-development characteristics on metro station usage: A case study of Tehran's metro stations and TOD index calculation. *Cities, 148*, 104840. https://doi.org/10.1016/j.cities.2024.104840

Kim, D., & Tepe, E. (2026). Estimating the impacts of climate change risk perception on local housing market: A case study in Miami-Dade, Florida. *Cities, 169*, 106517. https://doi.org/10.1016/j.cities.2025.106517

Kim, E. J., & Kim, H. (2020). Neighborhood walkability and housing prices: A correlation study. *Sustainability, 12*(2), 593–611. https://doi.org/10.3390/su12020593

Kim, J. H., Li, W., Newman, G., Kil, S. H., & Park, S. Y. (2018). The influence of urban landscape spatial patterns on single-family housing prices. *Environment and Planning B: Urban Analytics and City Science, 45*(1), 26–43. https://doi.org/10.1177/0265813516663932

Kopczewska, K., & Ćwiakowski, P. (2021). Spatio-temporal stability of housing submarkets: Tracking spatial location of clusters of geographically weighted regression estimates of price determinants. *Land Use Policy, 103*, 105292. https://doi.org/10.1016/j.landusepol.2021.105292

Koramaz, T. K., & Dökmeci, V. (2012). Spatial determinants of housing price values in Istanbul. *European Planning Studies, 20*(7), 1221–1237. https://doi.org/10.1080/09654313.2012.673569

Kortas, F., Grigoriev, A., & Piccillo, G. (2022). Exploring multi-scale variability in hotspot mapping: A case study on housing prices and crime occurrences in Heerlen. *Cities, 128*, 103814. https://doi.org/10.1016/j.cities.2022.103814

Kördiş, G., Işık, S., & Mert, M. (2014). The estimation of determinants of house prices in Antalya: Hedonic pricing model. *Akdeniz İİBF Journal, 14*(28), 103–132.

Law, S., Penn, A., Karimi, K., & Shen, Y. (2017, July). The economic value of spatial network accessibility for UK cities: A comparative analysis using the hedonic price approach. *Proceedings of the 11th International Space Syntax Symposium 2017* (Vol. 11, pp. 77-1). Instituto Superior Técnico.

Lee, H., Han, H., & Pettit, C. (2025). Capturing the distance decay effect of amenities on housing price using explainable artificial intelligence. *Applied Geography, 174*, 103486. https://doi.org/10.1016/j.apgeog.2024.103486

Li, H., Wei, Y. D., Wu, Y., & Tian, G. (2019). Analyzing housing prices in Shanghai with open data: Amenity, accessibility and urban structure. *Cities, 91*, 165–179. https://doi.org/10.1016/j.cities.2018.11.016

Li, M., Kwan, M. P., Hu, W., Li, R., & Wang, J. (2023). Examining the effects of station-level factors on metro ridership using multiscale geographically weighted regression. *Journal of Transport Geography, 113*, 103720. https://doi.org/10.1016/j.jtrangeo.2023.103720

Li, R. Y. M., Cheng, K. Y., & Shoaib, M. (2018). Walled buildings, sustainability, and housing prices: An artificial neural network approach. *Sustainability, 10*(4), 1298. https://doi.org/10.3390/su10041298

Liebelt, V., Bartke, S., & Schwarz, N. (2019). Urban green spaces and housing prices: An alternative perspective. *Sustainability, 11*(13), 3707. https://doi.org/10.3390/su11133707

Lieske, S. N., van den Nouwelant, R., Han, J. H., & Pettit, C. (2021). A novel hedonic price modelling approach for estimating the impact of transportation infrastructure on property prices. *Urban Studies, 58*(1), 182–202. https://doi.org/10.1177/0042098019879382

Lin, W. S., Tou, J. C., Lin, S. Y., & Yeh, M. Y. (2014). Effects of socioeconomic factors on regional housing prices in the USA. *International Journal of Housing Markets and Analysis, 7*(1), 30–41. https://doi.org/10.1108/IJHMA-11-2012-0056

Lisi, G. (2019). Sales comparison approach, multiple regression analysis and the implicit prices of housing. *Journal of Property Research, 36*(3), 272–290. https://doi.org/10.1080/09599916.2019.1651755

Liu, G., Wang, X., Gu, J., Liu, Y., & Zhou, T. (2019). Temporal and spatial effects of a 'Shan Shui' landscape on housing price: A case study of Chongqing, China. *Habitat International, 94*, 102068. https://doi.org/10.1016/j.habitatint.2019.102068

Liu, T., Wang, J., Liu, L., Peng, Z., & Wu, H. (2025). What are the pivotal factors influencing housing prices? A spatiotemporal dynamic analysis across market cycles from upturn to downturn in Wuhan. *Land, 14*(2), 356. https://doi.org/10.3390/land14020356

Liu, X., Chen, X., Orford, S., Tian, M., & Zou, G. (2024). Does better accessibility always mean higher house prices? *Environment and Planning B: Urban Analytics and City Science, 51*(9), 2179–2195. https://doi.org/10.1177/23998083241242212

Lu, B., Ge, Y., Shi, Y., Zheng, J., & Harris, P. (2023). Uncovering drivers of community-level house price dynamics through multiscale geographically weighted regression: A case study of Wuhan, China. *Spatial Statistics, 53*, 100723. https://doi.org/10.1016/j.spasta.2022.100723

Luo, L., Yang, X., Li, J., Song, Y., & Zhao, Z. (2025). Deciphering house prices by integrating street perceptions with a machine-learning algorithm: A case study of Xi'an, China. *Cities, 156*, 105542. https://doi.org/10.1016/j.cities.2024.105542

McCord, M., Lo, D., Davis, P. T., Hemphill, L., McCord, J., & Haran, M. (2020). A spatial analysis of EPCs in the Belfast Metropolitan Area housing market. *Journal of Property Research, 37*(1), 25–61. https://doi.org/10.1080/09599916.2019.1697345

Mills, E. S. (1972). *Studies in the structure of the urban economy*. Johns Hopkins Press.

Moralı, O., & Yılmaz, N. (2020). Spatial heterogeneity in Istanbul housing market: A geographically weighted approach. *Journal of Economics Finance and Accounting, 7*(4), 298–307. https://doi.org/10.17261/Pressacademia.2020.1304

Muth, R. F. (1969). *Cities and housing: The spatial pattern of urban residential land use*. University of Chicago Press.

Noh, C. S., Hyun, M. K., & Yoo, S. H. (2025). Residential heating method and housing prices: Results of an empirical analysis in South Korea. *Energies, 18*(14), 3809. https://doi.org/10.3390/en18143809

Önder, K., & Turgut, H. (2018). Examination of the factors affecting household rental housing demand through data mining. *Eskişehir Osmangazi University Journal of Economics and Administrative Sciences, 13*(2), 227–238. https://doi.org/10.17153/oguiibf.417717

Özüduru, B., & Yücesoy, E. Ü. (2018). The relationship between urban morphology and housing prices: Modeling through Ankara's road network design [Kent Morfolojisi ile konut fiyatları arasındaki ilişki: Ankara yol ağı tasarımı üzerinden modelleme]. *Türkiye Kentsel Morfoloji Ağı*, 369–381.

Payton, S. B., & Ottensmann, J. R. (2015). The implicit price of urban public parks and greenways: A spatial-contextual approach. *Journal of Environmental Planning and Management, 58*(3), 495–512. https://doi.org/10.1080/09640568.2013.864619

Porta, S., Strano, E., Iacoviello, V., Messora, R., Latora, V., Cardillo, A., Wang, F., & Scellato, S. (2009). Street centrality and densities of retail and services in Bologna, Italy. *Environment and Planning B: Planning and Design, 36*(3), 450–465. https://doi.org/10.1068/b34098

Pozo, A. M. M., Priesmeier, P., & Fekete, A. (2025). Measuring spatial accessibility to critical infrastructure: The Access Road Identification model. *International Journal of Critical Infrastructure Protection, 49*, 100760. https://doi.org/10.1016/j.ijcip.2025.100760

Sadayuki, T. (2018). Measuring the spatial effect of multiple sites: An application to housing rent and public transportation in Tokyo, Japan. *Regional Science and Urban Economics, 70*, 155–173. https://doi.org/10.1016/j.regsciurbeco.2018.03.002

Samad, N. S., Abdul-Rahim, A. S., Mohd Yusof, M. J., & Tanaka, K. (2020). Assessing the economic value of urban green spaces in Kuala Lumpur. *Environmen-*

tal Science and Pollution Research, 27(10), 10367–10390. https://doi.org/10.1007/s11356-019-07593-7

Saphores, J. D., & Aguilar-Benitez, I. (2005). Smelly local polluters and residential property values: A hedonic analysis of four Orange County (California) cities. *Estudios Económicos*, 197–218. https://doi.org/10.24201/ee.v20i2.163

Sayın, Z. M., Elburz, Z., & Duran, H. E. (2022). Analyzing housing price determinants in Izmir using spatial models. *Habitat International, 130*, 102712. https://doi.org/10.1016/j.habitatint.2022.102712

Selim, H. (2009). Determinants of house prices in Turkey: Hedonic regression versus artificial neural network. *Expert Systems with Applications, 36*(2), 2843–2852. https://doi.org/10.1016/j.eswa.2008.01.044

Shi, S., & Naylor, M. (2023). Perceived earthquake risk in housing purchases. *Journal of Housing and the Built Environment, 38*(3), 1761–1787. https://doi.org/10.1007/s10901-023-10012-6

Simpson, W. (1992). *Urban structure and the labour market*. Oxford University Press.

Sisman, S., & Aydinoglu, A. C. (2022). A modelling approach with geographically weighted regression methods for determining geographic variation and influencing factors in housing price: A case in Istanbul. *Land Use Policy, 119*, 106183. https://doi.org/10.1016/j.landusepol.2022.106183

Soegianto, L. M., Hinandra, A. T., Suri, P. A., & Fajar, M. (2024). Comparison of model performance on housing business using linear regression, random forest regressor, SVR, and neural network. *Procedia Computer Science, 245*, 1139–1145. https://doi.org/10.1016/j.procs.2024.10.343

Soltani, A., Lee, C. L., Mirzaie, R., & Qadikolaei, M. R. (2026). Environmental drivers of housing prices and thermal inequality using satellite imagery: A submarket approach. *Habitat International, 167*, 103628. https://doi.org/10.1016/j.habitatint.2025.103628

Srour, I. M., Kockelman, K. M., & Dunn, T. P. (2002). Accessibility indices: Connection to residential land prices and location choices. *Transportation Research Record, 1805*(1), 25–34. https://doi.org/10.3141/1805-04

Strohbach, M. W., Arnold, E., & Haase, D. (2012). The carbon footprint of urban green space—A life cycle approach. *Landscape and Urban Planning, 104*(2), 220–229. https://doi.org/10.1016/j.landurbplan.2011.10.013

Tan, R., Zhou, K., & Xu, H. (2019). Effects of urban road centrality on property values: Spatial hedonic analysis of the housing market in Wuhan, China. *Journal of Urban Planning and Development, 145*(2), 05019005. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000507

Tchuente, D., & Nyawa, S. (2022). Real estate price estimation in French cities using geocoding and machine learning. *Annals of Operations Research, 308*(1), 571–608. https://doi.org/10.1007/s10479-021-03932-5

Terzi, F., Dursun, D., Yilmaz, S., Erdem-Okumus, D., & Mutlu, B. E. (2025). Assessment of urban design scenarios from a microclimatic perspective and recommendations for climate-sensitive urban design in a new residential site. In *Environmentally sustainable and socially resilient urban development and management* (pp. 705–742). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-92850-5_30

Tian, G., Wei, Y. D., & Li, H. (2017). Effects of accessibility and environmental health risk on housing prices: A case of Salt Lake County, Utah. *Applied Geography, 89*, 12–21. https://doi.org/10.1016/j.apgeog.2017.09.010

Tomal, M. (2020). Modelling housing rents using spatial autoregressive geographically weighted regression: A case study in Cracow, Poland. *ISPRS International Journal of Geo-Information, 9*(6), 346. https://doi.org/10.3390/ijgi9060346

Tsai, I. C. (2018). Housing price convergence, transportation infrastructure and dynamic regional population relocation. *Habitat International, 79*, 61–73. https://doi.org/10.1016/j.habitatint.2018.07.004

TurkStat. (2025). *Building permit statistics*. Retrieved December 30, 2025, from https://biruni.tuik.gov.tr/medas/?kn=135&locale=tr

Türel, A. (1981). Ankara'da konut fiyatlarının mekansal farklılaşması. *METU Journal of the Faculty of Architecture, 1*(7), 97–109.

Uğurlar, A., & Eceral, T. Ö. (2014). An evaluation of the current housing market (home ownership and rental) in Ankara. *İdealkent, 5*(12), 132–159.

Wang, D., Li, V. J., & Yu, H. (2020). Mass appraisal modeling of real estate in urban centers by geographically and temporally weighted regression: A case study of Beijing's core area. *Land, 9*(5), 143. https://doi.org/10.3390/land9050143

Wang, Z., Wang, Y., Wu, S., & Du, Z. (2022a). House price valuation model based on geographically neural network weighted regression: The case study of Shenzhen, China. *ISPRS International Journal of Geo-Information, 11*(8), 450. https://doi.org/10.3390/ijgi11080450

Wang, Z., Wang, Y., Xia, X., Chen, S., & Jiang, W. (2025). How does built environment influence housing prices in large-scale areas? An interpretable machine learning method by considering multi-dimensional accessibility. *ISPRS International Journal of Geo-Information, 14*(11), 436. https://doi.org/10.3390/ijgi14110436

Wang, Z., Zhao, Y., & Zhang, F. (2022b). Simulating the spatial heterogeneity of housing prices in Wuhan, China, by regionally geographically weighted regression. *ISPRS International Journal of Geo-Information, 11*(2), 129. https://doi.org/10.3390/ijgi11020129

Wong, S. K., Chau, K. W., Yau, Y., & Cheung, A. K. C. (2011). Property price gradients: The vertical dimension. *Journal of Housing and the Built Environment, 26*(1), 33–45. https://doi.org/10.1007/s10901-010-9203-8

Wu, C., Ren, F., Hu, W., & Du, Q. (2019). Multiscale geographically and temporally weighted regression: Exploring the spatiotemporal determinants of housing prices. *International Journal of Geographical Information Science, 33*(3), 489–511. https://doi.org/10.1080/13658816.2018.1545158

Xiao, Y., Hui, E. C., & Wen, H. (2019). Effects of floor level and landscape proximity on housing price: A hedonic analysis in Hangzhou, China. *Habitat International, 87*, 11–26. https://doi.org/10.1016/j.habitatint.2019.03.008

Xiao, Y., Webster, C., & Orford, S. (2016). Identifying house price effects of changes in urban street configuration: An empirical study in Nanjing, China. *Urban Studies, 53*(1), 112–131. https://doi.org/10.1177/0042098014560500

Yang, J., Bao, Y., Zhang, Y., Li, X., & Ge, Q. (2018). Impact of accessibility on housing prices in Dalian city of China based on a geographically weighted regression model. *Chinese Geographical Science, 28*(3), 505–515. https://doi.org/10.1007/s11769-018-0954-6

Yang, Y., Dai, H. M., Chao, C. H., Wei, S., & Yang, C. F. (2023). Training a neural network to predict house rents using artificial intelligence and deep learning. *Sensors & Materials, 35*, 4671–4680. https://doi.org/10.18494/SAM4594

Ye, Y., Xie, H., Fang, J., Jiang, H., & Wang, D. (2019). Daily accessed street greenery and housing price: Measuring economic performance of human-scale streetscapes via new urban data. *Sustainability, 11*(6), 1741. https://doi.org/10.3390/su11061741

Yilmazer, S., & Kocaman, S. (2020). A mass appraisal assessment study using machine learning based on multiple regression and random forest. *Land Use Policy, 99*, 104889. https://doi.org/10.1016/j.landusepol.2020.104889

Yiu, C. Y., & Cheung, K. S. (2022). The age–period–cohort problem in hedonic house prices models. *Econometrics, 10*(1), 4–15. https://doi.org/10.3390/econometrics10010004

Yuan, F., Wu, J., Wei, Y. D., & Wang, L. (2018). Policy change, amenity, and spatiotemporal dynamics of housing prices in Nanjing, China. *Land Use Policy, 75*, 225–236. https://doi.org/10.1016/j.landusepol.2018.03.045

Zahirovich-Herbert, V., & Gibler, K. M. (2014). The effect of new residential construction on housing prices. *Journal of Housing Economics, 26*, 1–18. https://doi.org/10.1016/j.jhe.2014.06.003

Zambrano-Monserrate, M. A., Ruano, M. A., Yoong-Parraga, C., & Silva, C. A. (2021). Urban green spaces and housing prices in developing countries: A two-stage quantile spatial regression analysis. *Forest Policy and Economics, 125*, 102420. https://doi.org/10.1016/j.forpol.2021.102420

Zhang, D., Ji, Q., Zhao, W. L., & Horsewood, N. J. (2021). Regional housing price dependency in the UK: A dynamic network approach. *Urban Studies, 58*(5), 1014–1031. https://doi.org/10.1177/0042098020943489

Zhang, Q. (2021). Housing price prediction based on multiple linear regression. *Scientific Programming, 2021*(1), 7678931. https://doi.org/10.1155/2021/7678931

Zhang, S., Wang, L., & Lu, F. (2019a). Exploring housing rent by mixed geographically weighted regression: A case study in Nanjing. *ISPRS International Journal of Geo-Information, 8*(10), 431. https://doi.org/10.3390/ijgi8100431

Zhang, X., Zheng, Y., Sun, L., & Dai, Q. (2019b). Urban structure, subway systemand housing price: Evidence from Beijing and Hangzhou, China. *Sustainability, 11*(3), 669. https://doi.org/10.3390/su11030669

Zou, G., Lai, Z., Li, Y., Liu, X., & Li, W. (2022). Exploring the nonlinear impact of air pollution on housing prices: A machine learning approach. *Economics of Transportation, 31*, 100272. https://doi.org/10.1016/j.ecotra.2022.100272

Megaron, Vol. 21, No. 1, pp. 62–74, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.14602

Article

Studentification through a Turkish planning lens: Geographical and regulatory insights

Özge Erbaş Melis[1], Duygu Okumuş Prini[2]

[1]*Department of City and Regional Planning, İzmir Katip Çelebi University, Izmir, Türkiye*
[2]*Independent Researcher, Southsea, England*

ARTICLE INFO

Article history
Received: 8 January 2025
Revised: 20 February 2026
Accepted: 20 February 2026

Key words:
Gentrification; HMOs; Izmir; planning policies; studentification.

ABSTRACT

The concept of *studentification*, often discussed as a form of gentrification, has been predominantly studied in the United Kingdom, the United States, and Canada, where globally prominent universities and market-driven higher education systems prevail. While recent studies have begun to introduce geographical diversity, the planning dimensions of studentification remain underexplored. This paper examines the dynamics of studentification in the case of İzmir Katip Çelebi University in İzmir, Türkiye, highlighting differences between the Anglophone literature (UK, US, Canada) and the Turkish contexts. In Türkiye, rapid university expansion, limited state-provided accommodation, and a planning system that has yet to integrate student housing into its strategic framework have shaped distinct conditions for studentification. The findings indicate that local authorities have not developed proactive, plan-led responses, and strategic and spatial plans lack measures to address the social and spatial consequences of the growing student population. Drawing insights from the United Kingdom, the United States, and Canada, this paper proposes recommendations to enhance regulatory frameworks, strengthen compliance standards, and support municipalities in addressing the challenges of studentification in Türkiye.

Cite this article as: Erbaş Melis, Ö., & Prini Okumuş, D., (2026). Studentification through a Turkish planning lens: Geographical and regulatory insights. Megaron, 21(1):62–74.

INTRODUCTION

Türkiye's public university expansion has started since 2006 (Karatas Acer & Güçlü, 2017). As a part of this policy, İzmir Katip Çelebi University was established in 2010 as a public university. The university's main campus was established in Balatçık neighbourhood of Çiğli district 2010. Since then, the neighbourhood's population has more than doubled as of 2023 (TUIK, 2024). The percentage change in population highlights the significant increase in Balatçık's population compared to both Çiğli (29.85%) and the overall population of İzmir (11.29%) (TUIK, 2024). Notably, this peak occurred during the 2011-2012 period, coinciding with the

*Corresponding author
*E-mail adress: ozge.erbas@ikc.edu.tr

establishment of the university. The student population and their evolving needs are becoming increasingly apparent with each passing day. In response to this growing awareness, this research delves into the phenomenon of studentification in Türkiye, aiming to uncover its unique characteristics, disparities, and potential parallels with countries such as the UK, US, and Canada. The research places a particular focus on critical aspects such as urban planning, regulatory frameworks, and the roles played by local and central governments, shedding light on how these elements intersect to shape the experiences of student communities and their broader impact on urban landscapes.

STUDENTIFICATION IN PLANNING ASPECT

The concept of studentification as a distinct subcategory in the gentrification literature refers to the social, cultural, economic, and physical transformations that occur in a neighbourhood by the demographic shift driven by the influx of students into the area (Smith, 2002; Smith & Holt, 2007; Smith et al., 2014).

The physical changes brought about by studentification are often linked to transformations in the existing housing stock, increasing demand for new buildings and infrastructure, and degradation (Smith & Holt, 2007; Smith et al., 2014; Sage et al., 2012b; Revington et al., 2020). Higher education institutions play a pivotal role in driving local economic growth, though the scale and nature of their impact vary depending on the size of the city while in smaller towns, the local economy often becomes heavily reliant on student populations. Notable economic effects of studentification include increased property values and rental prices, as well as the diversification and expansion of local economic activities (Hubbard, 2008; Fabula et al., 2017; Sage et al., 2013; Smith et al., 2014).

However, this economic uplift often leads to social and economic polarisation. Rising property prices can displace long-term residents, exacerbating inequalities and reinforcing studentification as a subset of gentrification (Rugg et al., 2004; Smith, 2004; Sage et al., 2012b; Revington et al., 2020).

This reorganisation of local economies and the tensions with long-term residents lead to the marginalisation of non-student residents, reducing their sense of belonging and causing social fragmentation, and even the displacement of non-student residents, especially families and the elderly (Chatterton, 2000; Smith & Holt, 2007; Bromley, 2006; Foote, 2017).

One of the most focused aspects of studentification is the changes in the housing stock. In areas with a high concentration of student population, properties are frequently adapted to meet student needs, with single-family houses converted into shared accommodations where individual rooms are rented separately or new developments are designed and built for multiple-occupancy (Allinson, 2006; Garmendia et al., 2012; Hubbard, 2008; Grabkowska & Frankowski, 2016; Situmorang et al., 2019). In the UK, the phenomenon is often discussed alongside concepts such as “Housing in Multiple Occupations” (HMO) and “Purpose-Built Student Accommodation” (PBSA), given their prevalence in student-dense neighbourhoods (Sage et al., 2012a, 2013; Smith & Holt, 2007; Kinton et al., 2016, 2018; Hubbard, 2008).

The phenomenon of studentification necessitates a range of mitigation strategies tailored to the unique contexts of cities experiencing these challenges (Hubbard, 2008). In the UK, where student accommodation patterns have substantially altered urban landscapes, Part 2 of the UK Government Legislation (2004) mandates licensing for HMOs to regulate shared student housing, ensuring safety and quality while controlling its density in specific areas (Sage et al., 2012b; Kinton et al., 2016). PBSAs are increasingly encouraged as a solution to relieve pressure on traditional housing stocks while offering students tailored accommodations (Smith & Holt, 2007; Kinton et al., 2018). In cities like Durham, additional measures restrict the conversion of single-family homes to HMOs, dispersing student housing and promoting PBSAs (Wilkinson & Greenhalgh, 2022). While it is seen as a key player in managing student-related disruptions and improving housing satisfaction for long-term residents (Smith & Holt, 2007; Kinton et al., 2018), such policies have also faced criticism for being reactive and potentially escalating property values in student-heavy areas while devaluing non-student properties (Revington et al., 2020) and creating isolation for some students and causing segregation between students and local communities (Fincher & Shaw, 2009; Smith & Hubbard, 2014).

As documented by Revington et al. (2020) Waterloo in Canada took a multi-phased adaptation approach to studentification. Initial measures, such as the 1986 lodging house bylaw, introduced limits on unrelated occupants in single-family homes and minimum distance requirements between lodging houses. Later strategies focused on higher-density developments in designated zones by creating nodes and corridors to accommodate growing student populations while preserving low-density neighbourhoods (Revington et al., 2020). Although these policies effectively increased student housing capacity and diversified options, they struggled to reverse the conversion of owner-occupied homes in adjacent neighbourhoods, indicating the complex interplay of urban planning and market dynamics (Revington et al., 2020; Hubbard, 2008).

In South Africa, rapid university expansions and limited infrastructure created a different set of challenges (Gbadegesin et al., 2021). The 2015 norms and standards policy sought to address overcrowding through budget allocations for on-campus housing and accreditation of off-campus accommodations. While these initiatives aimed to improve living conditions and mitigate the adverse effects of studentification, they also underscored the difficulty of achieving ambitious targets, such as housing 80% of full-time students on campus (Gbadegesin et al., 2021).

Emerging trends in urban planning reflect a shift toward integrating student accommodations into broader community revitalisation efforts (Livingstone et al., 2023). For instance, local councils in the UK are increasingly zoning areas for PBSAs while encouraging brownfield regeneration to mitigate the oversupply and concentration of student populations (Hubbard, 2009). Similarly, Waterloo's adoption of mixed-use developments, enhanced public spaces, and sustainable transport links exemplifies a holistic response to studentification (Revington et al., 2020). These strategies aim to balance the needs of students, long-term residents, and urban ecosystems, fostering communities that are socially and economically resilient (Hubbard, 2009; Livingstone et al., 2023).

Although the impacts of universities in the regions and cities where they are located have been researched in Türkiye since the mid-1990s (Savaş Yavuzçehre, 2016; Atik, 1999; Görkemli, 2009; Öztürk et al., 2011; Akçakanat et al., 2010; Işık, 2008; Öztürk et al., 2009), the concept of studentification, as a subfield of gentrification literature, has remained quite limited in Türkiye's academic discourse. Tuncer & İslam (2017) examined the evolving relationships between students and residents over time in Konya. Kırmızı et al. (2020) focused on the process of studentification by documenting the changing physical and social structure of the area in Samsun. Aslan & Çakır (2021) examined the spatial and social transformation in the rural neighbourhoods of Hatay. However, none of the existing studies on studentification in Türkiye address how local governments manage this process, the measures they implement, or the role it plays in urban planning. This research seeks to enhance the conceptual understanding of studentification by examining it through the lens of Turkish urban planning. It aims to contribute to the broader academic discourse with an empirical study that highlights geographical and planning distinctions compared to urban planning contexts in the UK, the US, and Canada.

CONTEXTUAL FRAMEWORK

The contextual framework is structured to provide a comprehensive explanation of the Turkish higher education system alongside the planning system, offering a detailed foundation for understanding the dynamics at play before delving into the case study.

Higher Education in Türkiye

Law No. 2809, amended in 2006 by Law No. 5467, mandated establishing at least one higher education institution in each province, driving a rapid expansion of universities to enhance accessibility (Karataş Acer & Güçlü, 2017). Following this, student enrollment grew from 471,000 in 1990 to 6.5 million by 2024, fueled by the rise in public universities. The number of universities increased from 53 in the 1990s to 209 by 2024, with 131 being public (CoHE, 2024).

In the 2024-2025 academic year, Türkiye's higher education institutions serve 2.8 million associate and 3.7 million undergraduate students (CoHE, 2024). However, only 14.66% of students have access to state-subsidized accommodation, with dormitories housing 962,000 students across 850 buildings (KYK, 2024). This shortfall is compounded by a post-COVID-19 housing crisis[1], with housing prices in Izmir rising over 600% between 2020 and 2024 (Sahibinden, 2024).

Turkish Planning System

Every country has its own unique planning system, and its enforcement depends on their legislation. While some have advisory roles, some like the Turkish planning system have legally binding status. Law No. 3194 entered into force in 1985, and currently in force, is the backbone of the Turkish urban planning system. Based on Article 6 of the law, the Turkish planning system comprises upper- and lower-level plans (Law No. 3194, 1985). These plans are accepted as regulative administrative actions. Lower-level plans must align with and reflect the objectives of higher-level plans, with increasing levels of detail and specificity as one moves from the broader national framework to implementation plans. National Development Plans encompass strategic planning in all aspects of the nation, from education to urbanisation. However, the topics addressed in national development plans are not fixed for each planning period; they are adjusted based on both global and national contexts.

Higher Education in the Turkish Planning System at the National Level

The backbone of national-level planning is five-year development plans. Türkiye has had eleven 5-year development plans since 1963 (Presidency of the Republic of Türkiye, Directorate of Strategy and Budget, 2024). These plans, while establishing a long-term vision, also aim to identify challenges and develop strategies to address them. Including the expansion of higher education capacity and student accommodations topics closely linked to urban planning are examined. However, aspects such as curriculum design, education policies, and budgeting are excluded from consideration.

1 Due to the rising number of universities and the ongoing housing crisis, a significant number of students have increasingly opted to attend universities located in their parents' cities. In the case study case, approximately 30% of the enrolled students' family houses are located in Izmir (Yokatlas, 2024).

The plans reflect an ongoing focus on expanding higher education capacity and ensuring equal access across the country. Early plans emphasised expanding and distributing higher education institutions nationwide and responding to the growing demand for higher education. The Fourth and the Fifth plans highlighted the need for balanced distribution and capacity expansion, which had not been fully achieved in previous periods. The Seventh Development Plan (1996-2000) emphasises expanding the capacity of higher education institutions while also permitting the establishment of private universities. The Ninth Five Development Plan (2007-2012) underlines the same trend regarding higher education; the intense demand for higher education continues to increase. The Tenth Five Development Plan (2014-2018) explains the extension of higher education opportunities. During the Ninth Development Plan period, 36 state and 41 foundation (private) universities were established, bringing the total number of universities to 170 by May 2013.

The case study area for this research, Balatçık, hosts the main campus of İzmir Katip Çelebi University, established in 2011, reflecting the expansion of higher education opportunities. In addition to that, the capacities of the existing programmes are increased as well. The Eleventh Development Plan (2019-2023) highlights the international dimension of higher education. It aims to expand the number of programs offered in foreign languages, enhance accommodation opportunities for international students, and strengthen institutional capacity for internationalisation. As previously noted, the United Kingdom and the United States possess highly commercialisation of higher education systems catering to both national and international students. The Eleventh Development Plan (2019–2023) indicates a focus on internationalisation, which can be interpreted as an effort by Turkish higher education to move towards the commercialisation of the sector. Overall, the objectives of the development plans have primarily centred on two key areas since 1963: the nationwide distribution of universities and the expansion of their capacities, with a more recent emphasis on the internationalisation of higher education.

The policies regarding accommodation for higher education students in Türkiye's development plans reflect evolving priorities over time. The Second Plan (1970-1974) emphasises improving student dormitories to foster social interaction and cultural development. The Third Plan (1975-1979) highlights equitable access to education through loans, scholarships, and dormitory facilities, alongside social and healthcare services. The Fifth (1985-1989) and Sixth (1990-1994) Development Plans adopt a broader youth-centred approach, addressing housing alongside nutrition, health, and employment while promoting cultural values and responsibility. The Eleventh Plan (2019–2023) shifts its focus to internationalisation aiming to expand foreign language programs in parallel with enhancing accommodations for international students.

Higher Education in the Turkish Planning System at the Lower Level

Lower-level plans are zoning and implementation plans which are mandatory for district municipalities (Law No. 3194, Article 5). However, it needs to be highlighted that Türkiye does not have a 'single-family zoning' approach. Nevertheless, there are aspects of zoning that impact higher education and urban planning, such as regulations for dormitories and their site selection.

The law dated 14.06.2014 and numbered 29030 Regulation on the Preparation of Spatial Plans (2014) establishes the principles that related authorities must adhere to and also clarifies definitions and principles. The following two articles are related to educational facilities and dormitories as followings;

> *"5) i) Social infrastructure areas: This is a general term for public or private sector facilities aimed at meeting the cultural, social, and recreational needs of individuals and society, as well as enhancing quality of life and creating a healthy environment. It includes educational, health, religious, cultural, and administrative facilities, as well as open and green spaces such as open and closed sports facilities, parks, playgrounds, children's gardens, squares, and recreational areas"*

> *"j) Social facility area: These are areas, either publicly or privately owned, designated to provide services in functions aimed at enhancing the quality and level of social life for community benefits, such as daycare centres, courses, dormitories, nurseries, youth shelters, elderly and disabled care homes, rehabilitation centres, community centres, and shelters for those in need."*

These definitions raise two key issues. First, facilities may be owned by either public or private entities, yet they are collectively considered when determining the necessary space allocation. The inclusion of dormitories in planning documents does not necessarily imply that these facilities will be affordable. Secondly, student dormitories might not be explicitly included in the initial implementation plans under the title of dormitories but instead classified as *social infrastructure* or *social facility areas*. This lack of clarity and uncertainty can be seen in two ways: it may lead to a student housing crisis, or provide opportunities for flexibility in the planning process to adapt to emerging needs such as the growing demand for student housing.

METHODOLOGY

The existing research gap highlights that studies conducted not only in Türkiye but also in the world have not adequately addressed studentification from an urban planning perspective but primarily focused on human geography aspects of studentification. This research contributes to the literature as an original study by being one of the few studies focused on studentification in Türkiye (Tuncer & İslam, 2017; Kırmızı et al., 2020; Aslan & Çakır, 2021; Erbas Melis & Okumus Prini, 2023). However, these Turkish case studies have not thoroughly examined the concept of studentification from an urban planning perspective, nor have they provided specific recommendations for planning practice. Accordingly, the primary objective of this research is to analyse the dynamics of studentification from an urban planning perspective, emphasising the differences between the United Kingdom, the United States, Canada and the Turkish contexts. Based on this existing set-up raises the following questions: 1) 'How does studentification in Türkiye compare to what has been observed in the UK, the US, and Canada in terms of urban planning and policy?' and to contribute to the Turkish legislative and planning system, the research also focuses on the answer to the second question; 2) 'what specific urban planning strategies can local government authorities adopt to address the unique challenges posed by studentification process?".

This study employed a mixed-methods approach, integrating both the collection of primary documents and primary data (Figure 1). In the initial phase, primary documents, including upper and lower-level plans and state documents, were sourced from the Presidency of Strategy and Budget (previously the Ministry of Development), the Ministry of Youth and Sports and the Municipality of Çiğli. Primary data was gathered through semi-structured interviews with diverse stakeholders in the neighbourhood. These interviews were conducted across four distinct groups: local residents unaffiliated with the university (n=8), local businesses (n=9), real estate agencies (n=2), and representatives from local government (n=2). This range of stakeholders enabled the researchers to examine the process and impact of studentification from multiple perspectives to have suggestions for regulative purposes.

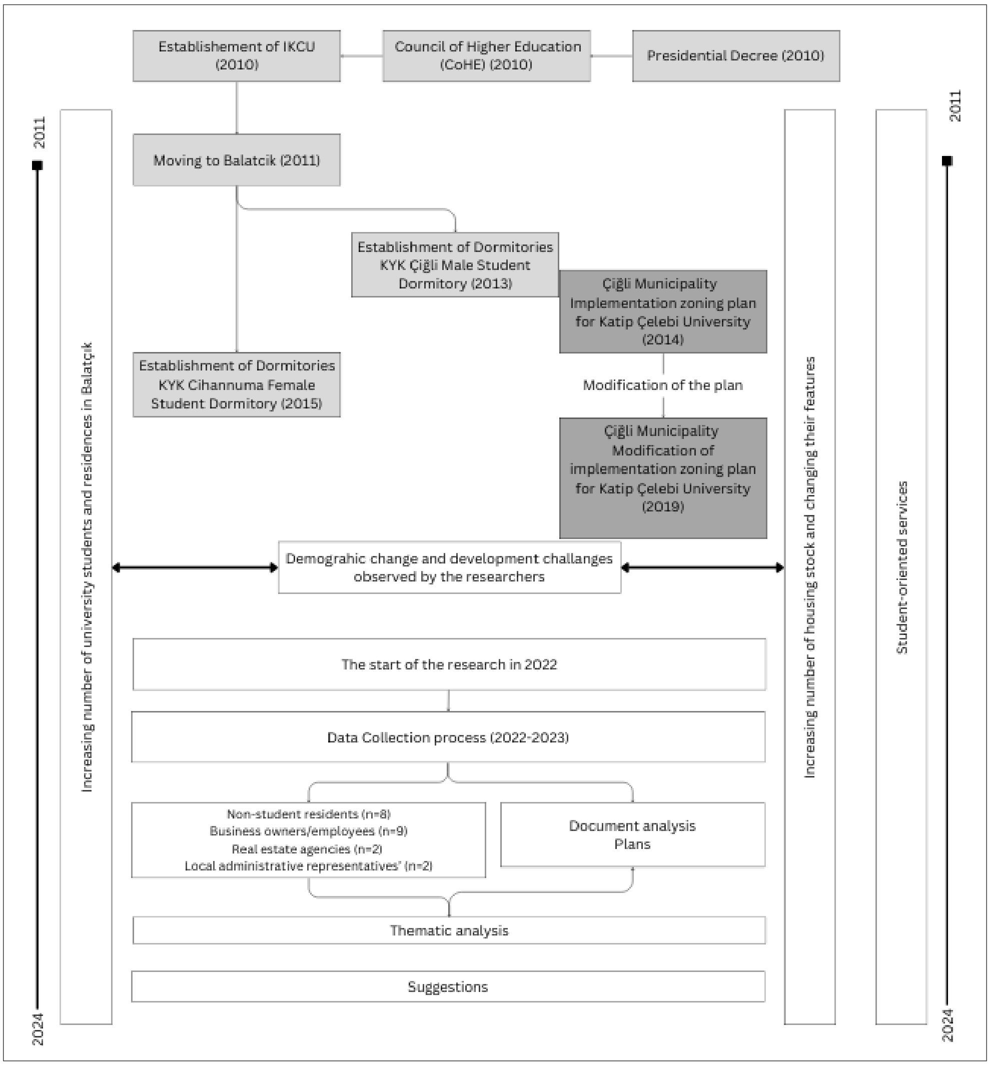

Figure 1. Thematic framework and research design.

The research deliberately targeted non-student stakeholders, including local residents, real estate agents, local businesses, and municipal authorities whose views and actions significantly shape urban development and planning responses. While the exclusion of student voices is acknowledged as a limitation, it was a strategic methodological choice aligned with the research aim: to understand how studentification is perceived, managed, and regulated by local actors beyond the student body.

For interviews with non-student local residents, the year of 2011 was identified as a significant benchmark, marking the establishment of İzmir Katip Çelebi University in the area. Consequently, residents were divided into two main groups: those residing in the neighbourhood before 2011 and those who moved in afterwards. Interviews with local businesses were evenly distributed across three categories: food and beverage establishments (restaurants and bars), retail stores, and personal service providers (hairdressers). Additionally, an interview was conducted with the Planning and Project Directorate of the Çiğli Municipality to gain insight into the local government's stance on studentification in the area.

After conducting the interviews, the qualitative data was analysed using a thematic analysis framework. The interview transcripts were first transcribed verbatim and then systematically coded. Including market-led development, planning, housing supply, housing demand, affordability, and student-focused policies. During axial coding, these were grouped into three major themes: Urban Governance, Housing Supply and Demand, and Planning Practices. Notably, several codes were identified as cross-cutting, informing more than one theme. Thematic patterns were compared across stakeholders: non-student residents, business owners/employees, real estate agents, and local government representatives. These comparisons helped to identify convergences and divergences in their perspectives on the outcome of the studentification process in the neighbourhood. This interconnected coding approach allowed for a more holistic interpretation of the studentification dynamics in the study area. Emerging themes were compared with the existing urban planning theories and the existing literature to contextualise the findings within a broader academic framework.

DISCUSSION: WHAT ARE THE DIFFERENCES BETWEEN THE EXISTING LITERATURE AND TURKISH CONTEXT?

As mentioned in the earlier section of this research, the existing literature on studentification has predominantly concentrated on the United Kingdom, the United States, and Canadian contexts. However, this research is conducted in a context where the same dynamics had not been prevalent until recent years. Consequently, the discussion section examines the differences between these countries and the Turkish context, with particular focus on urban development policies and planning systems. These key differences are categorised to highlight the distinct approaches and challenges faced in each context.

State-led Development vs. Market-led Development

In a state-led development, the state regulates urban development features, including site selection of the universities, dormitories, housing markets, and licensing. These are regulated with government controls; regulations and planning. However, in a market-led development, individual consumers and businesses lead the investments which impact urban development. This is possible with supply and demand and limited regulation. From this point of view, regulation and planning should be investigated in detail.

As mentioned earlier, the central and local governments play pivotal roles in shaping state-led development. Therefore, to get an insight view, an interview was conducted with a local government official who has been an urban planner in the responsible municipality for over 10 years.

> *"The 1/1000 implementation zoning plans for the north of Anadolu Avenue and Balatçık neighbourhood were approved in 1989, and the revision was approved in 1996. The plan approved in 2008 is currently in effect. The implementation zoning plan for İzmir Katip Çelebi [University] was approved in 2014, and the revision was approved in 2019."* (Local Government- Planner)

Based on the interview and documents obtained from the municipality, the local government implemented various plans to modify zoning regulations in response to evolving urban needs over time. However, these regulations have struggled to adapt to the rapidly emerging demands of the university and its students. Consequently, market forces have played a significant role in addressing the needs of university students.

Additionally, as explained earlier, student accommodation in Türkiye faces significant challenges, primarily due to the rapid increase in student enrolment at universities, with 1.1 million in 2000 and 6.5 million by 2024 (CoHE, 2024). As the demand for higher education has expanded, the need for affordable and adequate student housing has also risen sharply. However, the supply of public dormitories and other state-sponsored accommodations has not kept pace with the increase in demand. The case study university has no university-provided accommodation; however, two state-owned dormitories exist in the vicinity of the campus. These state-owned dormitories have a 2160-bed capacity, which not only serves İzmir Katip Çelebi University but also other universities in Izmir. Even though these are reserved for İzmir Katip Çelebi University, they only serve 12.29% of the undergraduates, as the total student population at the undergraduate level at İzmir Katip Çelebi University is 17,140

(IKCU, 2024a). Consequently, alternative housing options are required. As mentioned earlier, approximately 30% of the enrolled students' family houses are located in Izmir (Yokatlas, 2024). Based on this information, even with the new state-run dormitory, only 25% of the student population can be accommodated in these state-owned dormitories, underscoring the inadequacy of the public student housing supply. This means that 9000 students are in need of accommodation.

> *"The municipality has contributed little to the neighbourhood's development, which has so far relied on the efforts of local contractors. Despite owning numerous plots of land, the municipality has failed to utilise them effectively."* (B11-Realtor)

> *"There is nothing in the neighbourhood in terms of socio-cultural activities. There are only small playgrounds for children, and those do not serve adults."* (Non-student local resident-1)

> *"I don't spend much time in the neighbourhood because there aren't many recreational spaces."* (Non-student local resident-5)

> *"There is an inevitable need for [socio-cultural spaces]. People naturally want to see a recreational area in the place where they live. They want somewhere to socialise, a path where they can take a walk, but there isn't one. We are, so to speak, living among piles of concrete."* (Non-student local resident-6)

Based on these interviews, the municipality's limited involvement in the development process, particularly in urban planning and land use takes attention. It is claimed that the neighbourhood's change has been driven by market-led development rather than state-led initiatives. Additionally, despite owning numerous plots of land, the municipality has been criticised for not utilising these resources effectively to provide social-cultural and green infrastructure in favour of local residents.

During the interviews, local residents and business owners also identified infrastructure-related problems such as unpaved roads, insufficient street lighting and surface water drainage system. These problems typically occur when there is an imbalance between the rapid expansion of residential development and slower delivery of infrastructure by the local government. In parallel with this imbalance, residents and business owners express their dissatisfaction with municipal services in the neighbourhood.

> *"I'm not satisfied at all with the municipality's services. especially in our area, the part between the İZBAN station and Anadolu Street, we haven't seen any municipal services. In fact, since I moved here, the side road between my house and the İZBAN line was just a dirt road. Only a few months ago did they finally pave it with cobblestones, so at least now we're rid of the dust."* (Non-student local resident-4)

> *"This neighbourhood was a village before 2011. But even after the establishment of the university, the roads are still in terrible condition, the side streets are in bad shape, and there's still no proper infrastructure."* (Non-student local resident-8)

> *"The municipality isn't working hard enough. There's an infrastructure problem. When it rains, the roads become so bad that they're unusable."* (Local business-3)

> *"The [street] lighting in the neighbourhood is insufficient. The roads are constantly being built and then torn up again. The municipality is not working adequately."* (Local business-7)

The interview with the local government urban planner provides insight into the planning and zoning regulations related to student accommodation in the area. This interview helps to understand the existing and long-term development dynamics in the neighbourhood.

> "*Student dormitories appear as municipality facility areas or social facility areas in the plans, you need to look at the plan notes [to understand the intended use]. Also, according to Article 19, an entire independent section can be designated as a dormitory*[2] *if there is a commercial unit among residential units. This is also referred to as roadside commerce, and such decisions, even if not included in the plan, are made through a council resolution."* (Local Government - Planner)

According to the planner, student dormitories might not be explicitly included in the initial implementation plans, with such decisions being made by the local government. However, they might be constructed in areas that are designated as municipality facility areas or social facilities. In the same way, if a residential building on a commercial road is on the plan, it can be converted to a private dormitory without the need for a planning revision. This situation may be seen as uncertainty, leading to undesirable planning outcomes, such as a student housing crisis. Alternatively, it can introduce flexibility into the planning process, allowing regulations to be adapted to meet emerging needs, such as increased demand for student housing.

As observed in Waterloo in the early 2000s (Revington et al., 2020), leaving loopholes in the planning regulations to encourage the construction of more dormitories in certain areas could result in an oversupply of a specific type of housing stock, potentially leading to either an over-concentration of students or underutilised resources. At the moment, Balatçık is on the verge of an oversupply of one-bedroom apartment units. Based on construction permit data from 2011 to 2023, 66% of the housing units in the neighbourhood are one-bedroom, 29% are two-bedroom,

2 These dormitories are private dormitories which would be equivalent of PBSAs in Turkish context.

and 5% are three-bedroom flats (Erbas Melis et al., 2025), as will be discussed later in this paper.

The existing state-owned dormitories and their capacities are listed (Table 1). Based on that, it is not possible to access demand data regarding the percentage of the student population that applied for the 3,000-bed capacity state-run dormitory. CoHE reports indicate that 60% of the 17,000-student population comes from outside İzmir for university studies (CoHE, 2024; Yökatlas, 2024) which means that they need a type of accommodation. However, despite the construction of new dormitories to accommodate 1,000 more students, the supply will still fall short of meeting the increasing need. In this context, the term "demand" has been redefined as "need." Consequently, the gap between the supply and the need for accommodation persists as a significant challenge in providing adequate housing for students, with market-driven developments continuing to play a role in expanding accommodation options.

Plan-led Developments vs. Development-led Planning Practices

Plan-led development integrates the coordination of state-led and market-led initiatives, aiming to promote economic stability and foster social equity. In contrast, development-led planning arises as a response to significant changes driven by market pressures. A key distinction between the two approaches lies in their timeframes: plan-led development involves proactive planning before action, whereas development-led planning follows action (Figure 2). In this research, the rapid increase in one-bedroom accommodation units within the neighbourhood, aimed at addressing the demand for state-run dormitories with sufficient capacity, serves as an example of market-led development.

Due to the ongoing housing crisis in Izmir after the recent earthquakes and the growing need for student accommodation, developers have increasingly shifted their focus toward smaller, fewer-bedroom units, particularly one-bedroom flats. The development-led planning process has primarily responded to market pressures and immediate needs, rather than long-term strategies, by expanding the supply of such units.

Table 1. State-subsidised student accommodation

	Name of Accommodations	Opening Date	Capacity in 2024
State-Owned Dormitories	KYK Cihannuma Female Student Dormitory	2015	960
	KYK Çiğli Male Student Dormitory	2013	1200
	KYK Çiğli Dormitory	Under Construction	1000

Source: IKCU, 2024b

However, local planning authorities have not been proactive in pursuing plan-led development. They have neither coordinated with the university's site selection in the district nor developed strategies to mitigate the social and spatial consequences of student housing demand. The strategic and spatial plans of Çiğli Municipality and İzmir Metropolitan Municipality also lack specific measures to address the studentification process.

Insights from interviews further reveal an absence of comprehensive policy decisions and the lack of a roadmap to acknowledge and address the implications of the growing student population in the region.

> "*Rents are too high for public university students to afford, the recently built houses* [mainly one-bedroom flats] *are too small for students to share, and there are not enough dormitories where students can stay.*" (B10-Realtor)

> *"There's a high demand for rental housing, but it's difficult for students to find a place to stay. Student dormitories are needed in the neighbourhood."* (Non-student local resident-7)

> *"Very small flats [one-bedroom] are rented or sold for very high prices."* (Non-student local resident-1)

> *"The rent for a one-bedroom flat starts from 7,000 Turkish Liras (approx. 380 US Dollars as of March 2022) so, some students cannot afford to live in Balatçık. Also, there is a notable shortage of private dormitories in the neighbourhood. Therefore, some of these students prefer to live in Karşıyaka or Bornova in shared flats."* (Neighbourhood official)

The interviewees highlight the challenges related to student housing affordability and availability in the neighbourhood. A local realtor emphasised that rents are prohibitively high for public university students, and the newly built one-bedroom flats are too small to accommodate multiple students who would like to share an accommodation due to costs. As mentioned earlier, the number of state dormitories is not enough to accommodate students' housing need either. This highlights a critical issue: the need for comprehensive planning and investment in student accommodation at both national and local levels.

CONTEXT OF HMO LICENSING

As can be seen in the discussion, different regions of the world exhibit distinct dynamics in the studentification phenomenon. Therefore, from a holistic perspective, some suggestions are listed for mitigating the impacts of studentification in neighbourhoods while balancing the needs of the community within the Turkish planning system. National-level policies and development plans indicate a strategic move towards the internationalisation of higher education, which is expected to result in a significant increase in student numbers and the need for student accommodation. As previously noted in the contextual framework, accommo-

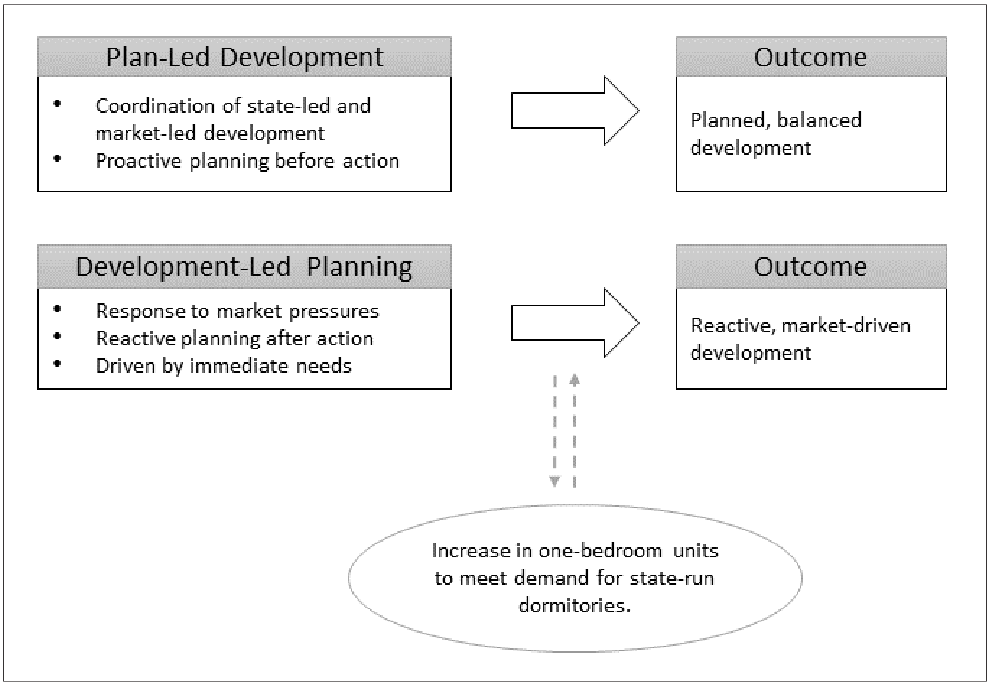

Figure 2. Plan-led development vs development-led planning.

dation options for higher education students (dormitories) within the Turkish planning system are addressed at the lower level through implementation plans. Consequently, local governments must be adequately prepared to address these changes. Therefore, the HMO recommendations presented in this section should be carried out within the scope of planning notes in these implementation plans, under the jurisdiction of district municipalities.

Need for HMO Licensing

Due to the increasing number of students in some neighbourhoods, local governments prefer to implement measures for neighbourhood stability to avoid social segregation among the non-student and student residences, relieve pressure on traditional housing stocks, and offer students tailored accommodations (Hubbard, 2008; Sage et al., 2012b; Kinton et al., 2016). Therefore, some countries, such as the UK, introduced licencing for HMOs.

As mentioned earlier, studentification has been a topic of planning in the UK. One of the most discussed topics is the licensing of houses in multiple occupations. The term, a house in multiple occupation (HMO), is described by the UK government as ‘a property rented out by at least 3 people who do not form a ‘household’ (for example, a family) but share facilities like the bathroom and kitchen’ (Gov.uk, 2022). In Türkiye, currently, students come together with prospective flatmates to rent a flat instead of individually renting a room from an HMO. When this research was conducted in 2022 and 2023, neither the central nor the local government had long-term strategies to control the student housing market in regards to licensing the housing for multiple occupants and regulating the housing supply in a given location. However, Türkiye does not have any legislation regarding HMOs. The lack of such legislation could lead to significant challenges for students, homeowners, non-student local residents and local government (Sage et al., 2012b; Kington et al., 2016).

When this research was conducted between 2022-2024, neither the Development Law nor relevant zoning regulations in Türkiye defined or governed shared rental arrangements. However, with the increasing number of students and in parallel to this, the rising demand for student housing has unearthed a housing supply and demand gap. Consequently, the subsequent section provides recommendations on the HMO licensing process from a planning perspective.

Planning Implications and Recommendations

The Turkish planning system and local governments should carefully consider studentification, evaluating both its potential advantages and disadvantages. Accordingly, this section outlines recommendations for structuring the HMO licensing implementation process to minimise adverse impacts while enhancing the potential benefits associated with studentification.

Local population should be adjusted to include HMO residents: It is important to note, however, that in some cases, students may not update their residential addresses when they move out of their family residences. This is also observed in the case study area, Balatçık. The students stated that they did not feel obligated to change their addresses and keep their family-based addresses. As a result, the Address-Based Population Registration System does not reflect temporary student residences; therefore, it complicates demographic analysis and public service provision.

The mandatory declaration of HMO-converted houses, along with their potential and actual occupancy data, ensures greater transparency in the HMO system and provides a valuable data source for population calculations. Similarly, in PBSA (Purpose-Built Student Accommodation) projects, the bed capacity is predetermined, offering a reliable basis for demographic estimations. Therefore, incorporating HMO and PBSA capacity data is essential to achieve more accurate and realistic population estimates in these neighbourhoods.

Integrating HMO Licenses into Implementation Plans: Even though, in general, it is thought that local authorities need to establish clear zoning and density regulations for HMOs, according to previous research, including the work by Revington et. al (2020), implementing uniform regulations in areas adjacent to higher education institutions may introduce additional challenges. For example, if regulatory measures are limited to a certain area with clear boundaries, HMOs may become concentrated just beyond the specified boundary, leading to unintended clustering effects. Therefore, HMO regulations should not be predominantly limited to an area with certain boundaries. Instead, it is important to consider these areas at the city level—particularly in metropolitan areas—due to the overlapping impact zones of multiple higher education centres.

Diversifying the Housing Mix: HMO licensing should be considered at two levels: The building block (yapı adası) and the individual structure. Following the calculation of projected population density over a 30-year period, adjustments could be introduced for neighbourhoods anticipated to experience heightened student populations as a result of studentification. Based on these adjusted population figures, corresponding HMO licensing requirements may be formulated. To promote balanced population diversity in both vertical and horizontal growth, it may be advisable to explore setting an indicative threshold—such as limiting licenses to approximately half of the properties within each city block and individual structure. This threshold, however, should be regarded as a preliminary suggestion and refined through further empirical research and policy evaluation.

In studentified or studentified-to-be neighbourhoods, municipalities should consider not only regulating HMOs but also the number of one-bedroom or studio flats. New housing policies should introduce a diverse housing mix, including larger, multi-bedroom units to prevent the over-saturation of single-occupancy residences and promote a balanced housing mix within the community. Such measures would ensure hosting a broader range of residents. Therefore, the total number of one-bedroom and studio flats should be limited to half of the properties within a building complex.

CONCLUSION AND FURTHER RESEARCH

This study has examined the dynamics of studentification in the case of İzmir Katip Çelebi University in İzmir, mainly focusing on understanding the differences between the United Kingdom, the United States, and Canadian context and the Turkish context. While studentification has been widely studied in these countries, its emergence in Türkiye reflects distinct conditions shaped by rapid university expansion, limited state-provided accommodation, and a planning system that has yet to fully integrate student housing and the increasing student population in areas surrounding campuses into its strategic framework. The findings indicate that local authorities have not developed proactive, plan-led responses regarding the studentification.

As elaborated in the discussion section, two main controversies emerge from this empirical research. Firstly, urban development regulated by government controls and planning has struggled to adapt to the rapidly growing demands of universities and their students. While adequate accommodation remains the most immediate and visible need, provisions for physical and socio-cultural infrastructure for the broader local population, including students, have also lagged behind market-driven developments. Secondly, plans intended to coordinate state-led and market-led initiatives, promote economic stability, and foster social equity in this rapidly evolving urban environment have largely yielded to market pressures that have resulted in an unbalanced housing supply. These findings suggest that without more proactive and coordinated planning, the pressures of studentification are likely to exacerbate social and spatial inequalities in the affected areas.

The comparison between the existing literature and Turkish contexts shows that, whereas these countries has implemented regulatory mechanisms such as HMO licensing to mitigate negative impacts, Türkiye still lacks a coherent policy framework. Introducing HMO licensing could help create more balanced and sustainable outcomes for both students and local residents. Accordingly, this research proposes several recommendations: adjusting local population data to account for HMO residents, integrating HMO licensing into implementation plans, and diversifying the housing mix to prevent over-reliance on single-occupancy units.

While this study has focused on the urban planning implications of studentification, future research could examine the wider socio-economic impacts of licensing practices. In particular, further work could assess how licensing influences population dynamics, housing markets, local economies, and social relations between student and non-student residents. Combining demographic and economic analysis with qualitative insights from local stakeholders would provide a fuller understanding of how licensing shapes neighbourhood change and its links to processes such as gentrification.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Akçakanat, T., Çarıkçı, İ., & Dulupçu, M. A. (2010). Economic contributions and spending tendencies of university students to the city center they are in: The case of Isparta 2003–2009 [Üniversite öğrencilerinin bulundukları il merkezine ekonomik katkıları ve harcama eğilimleri: Isparta 2003–2009 yılları örneği]. *SDÜ Fen Edebiyat Fakültesi Sosyal Bilimler Dergisi, 22*(2), 165–178.

Allinson, J. (2006). Over-educated, over-exuberant and over here? The impact of students on cities. *Planning Practice and Research, 21*(1), 79–94. https://doi.org/10.1080/02697450600901541

Aslan, A. S., & Çakır, B. (2021). An Analysis of the Current Dynamics of Soylulaştırma: The Process and Effects of 'Studentification' in the Serinyol/Antakya Case [Soylulaştırmanın güncel dinamiklerinin bir analizi: Serinyol/Antakya örneğinde "öğrencileştirme" süreci ve etkileri]. *Planlama, 31*(3), 546–561. https://doi.org/10.14744/planlama.2021.80270

Atik, H. (1999). Contributions of universities to the local economy: Theory and an application on Erciyes University [Üniversitelerin yerel ekonomiye katkıları: Teori ve Erciyes Üniversitesi üzerine bir uygulama]. *Erciyes Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 15*, 99–109.

Bromley, R. (2006). On and off campus: Colleges and universities as local stakeholders. *Planning Practice and Research, 21*(1), 1–24. https://doi.org/10.1080/02697450600901400

Chatterton, P. (2000). The cultural role of universities in the community: Revisiting the university–community debate. *Environment and Planning A, 32*(1), 165–181. https://doi.org/10.1068/a3243

CoHE (2024). Statistics [İstatistikler]. https://istatistik.yok.gov.tr/

Erbas Melis, O., & Okumus Prini, D. (2023). Understanding active mobility and micromobility in a studentified neighbourhood. *Online Journal of Art and Design, 11*(5), 212–230.

Erbaş Melis, Ö., Okumuş Prini, D., & Yılmaz, Y. İ. (2025). Transitioning from artichoke fields to a peri-urban settlement: The role of İzmir Katip Çelebi University. *ICONARP International Journal of Architecture and Planning, 13*(1), 121–144. https://doi.org/10.15320/ICONARP.2025.318

Fabula, S., Boros, L., Kovács, Z., Horváth, D., & Pál, V. (2017). Studentification, diversity and social cohesion in post-socialist Budapest. *Hungarian Geographical Bulletin, 66*(2), 157–173. https://doi.org/10.15201/hungeobull.66.2.5

Fincher, R., & Shaw, K. (2009). The unintended segregation of transnational students in central Melbourne. *Environment and Planning A, 41*(8), 1884–1902. https://doi.org/10.1068/a41126

Foote, N. S. (2017). Beyond studentification in United States college towns: Neighborhood change in the knowledge nodes, 1980–2010. *Environment and Planning A, 49*(6), 1341–1360. https://doi.org/10.1177/0308518X1769896

Garmendia, M., Coronado, J. M., & Ureña, J. M. (2012). University students sharing flats: When studentification becomes vertical. *Urban Studies, 49*(12), 2651–2668. https://doi.org/10.1177/004209801142817

Gbadegesin, J., Marais, L., Denoon-Stevens, S., Cloete, J., Venter, A., Rani, K., Lenka, M., Campbell, M., & Koetaan, Q. (2021). Studentification and governance in South Africa: Dependencies and conflicts. *Land Use Policy, 109*, 1–9. https://doi.org/10.1016/j.landusepol.2021.105639

Görkemli, H. N. (2009). Economic impacts of Selçuk University on the city of Konya. *Selçuk Üniversitesi Sosyal Bilimler Enstitüsü Dergisi, 22*, 169–186.

Gov.uk (2022). House in multiple occupation licence. Retrieved January 3, 2022, from https://www.gov.uk/house-in-multiple-occupation-licence.

Grabkowska, M., & Frankowski, J. (2016). "Close to the city centre, close to the university": Are there symptoms of studentification in Gdańsk, Poland? *Bulletin of Geography, 32*(32), 73–83. https://doi.org/10.1515/bog-2016-0016

Hubbard, P. (2008). Regulating the social impacts of studentification: A Loughborough case study. *Environment and Planning A, 40*(2), 323–341. https://doi.org/10.1068/a396

Hubbard, P. (2009). Geographies of studentification and purpose-built student accommodation: Leading separate lives? *Environment and Planning A: Economy and Space, 41*(8), 1903–1923. https://doi.org/10.1068/a4149

IKCU (2024a). *Student Statistics. [Öğrenci İstatistikleri]*. Retrieved November 11, 2024, from https://ubs.ikcu.edu.tr/bip/businessintelligence/Students/TotalStudents.

IKCU (2024b). *Yurt Kapasiteleri [Dormitory capacities]*. Retrieved March 3, 2025, from https://ikcu.edu.tr/S/16939/yurtlar#:~:text=%C3%9Cniversitemiz%20%C3%A7i%C4%9Fli%20ana%20 kamp%C3%BCs%C3%BCne%20500,kapasiteli%20erkek%20%C3%B6%C4%9Frenci%20yurduda%20bulunmaktad%C4%B1r

Işık, Ş. (2008). The effects of universities on urbanization in Turkey [Türkiye'de üniversitelerin kentleşme üzerine etkileri]. *Dokuz Eylül Üniversitesi Sosyal Bilimler Enstitüsü Dergisi, 10*(3), 159–181.

Karataş Acer, E., & Güçlü, N. (2017). An analysis of the expansion of higher education in Turkey using the new institutional theory. *Educational Sciences: Theory & Practice, 17*, 1911–1933. https://doi.org/10.12738/estp.2017.6.0031

Kinton, C., Smith, D. P., & Harrison, J. (2016). De-studentification: Emptying housing and neighbourhoods of student populations. *Environment and Planning A, 48*(8), 1617–1635. https://doi.org/10.1177/0308518X166424

Kinton, C., Smith, D. P., Harrison, J., & Culora, A. (2018). New frontiers of studentification: The commodification of student housing as a driver of urban change. *Geographical Journal, 184*(3), 242–254. https://doi.org/10.1111/geoj.12263

Kırmızı, M., Gürol, N., & Yıldız, H. (2020). The question of studentification in Samsun and its social effects [Samsun'da öğrencileştirme sorusu ve toplumsal etkileri]. *Sosyoloji Araştırmaları Dergisi, 23*(1), 61–93. https://doi.org/10.18490/sosars.728304

KYK (2024). *Dormitory Services [Yurt Hizmetleri].* Retrieved November 11, 2024, from https://kygm.gsb.gov.tr/Sayfalar/2434/2389/GenelBilgiler

Livingstone, N., Fiorentino, S., & Short, M. (2023). Density, planning, and the emergent landscapes of purpose-built student accommodation in England. *Frontiers in Sustainable Cities, 5,* 1119399. https://doi.org/10.3389/frsc.2023.1119399

Öztürk, S., Torun, İ. & Özkök, Y. (2011). Contributions of universities established in Anatolia to the socio-economic structure of the cities [Anadolu'da kurulan üniversitelerin illerin sosyo-ekonomik yapılarına katkıları]. *Mustafa Kemal Üniversitesi Sosyal Bilimler Enstitüsü Dergisi, 8*(16), 145–158.

Öztürk, S., Torun, İ., & Sayın, S. (2009). The university's impact on socio-economic development: The case of Kafkas University [Üniversitenin sosyo-ekonomik gelişmeye etkisi: Kafkas Üniversitesi örneği]. *İktisat Dergisi, 49*, 71–84.

Revington, N., Moos, M., Henry, J., & Haider, R. (2020). The urban dormitory: Planning, studentification, and the construction of an off-campus student housing market. *International Planning Studies, 25*(2), 189–205. https://doi.org/10.1080/13563475.2018.1552565

Rugg, J., Ford, J., & Burrows, R. (2004). Housing advantage? The role of student renting in the constitution of housing biographies in the United Kingdom. *Journal of Youth Studies, 7*(1), 19–34. https://doi.org/10.1080/1367626042000209930

Sage, J., Smith, D., & Hubbard, P. (2012a). The diverse geographies of studentification: Living alongside people not like us. *Housing Studies, 27*(8), 1057–1078. https://doi.org/10.1080/02673037.2012.728570

Sage, J., Smith, D., & Hubbard, P. (2012b). The rapidity of studentification and population change: There goes the (student)hood. *Population, Space and Place, 18*, 597–613. https://doi.org/10.1002/psp.690

Sage, J., Smith, D., & Hubbard, P. (2013). New-build studentification: A panacea for balanced communities? *Urban Studies, 50*(13), 2623–2641. https://doi.org/10.1177/0042098013477694

Sahibinden (2024). *İzmir Housing Prices per Square Meter*. Retrieved October 24, 2024, from https://www.sahibinden.com/emlak360/emlak-endeksi/konut/satilik/izmir/460/23625

Savaş Yavuzçehre, P. (2016). The impacts of universities on their cities: The case of Denizli Pamukkale University. [Üniversitelerin kentlerine etkileri: Denizli Pamukkale Üniversitesi örneği]. *Süleyman Demirel Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 21*(1), 235–250.

Situmorang, R., Antariksa, Surjono, & Wicaksono, A. D. D. (2019). The feasibility of Malang City as college town. *International Journal of Scientific and Technology Research, 8*(12), 2835–2839.

Smith, D. P. (2002). Extending the temporal and spatial limits of gentrification: A research agenda for population geographers. *International Journal of Population Geography, 8*(6), 385–394. https://doi.org/10.1002/ijpg.267

Smith, D. P., & Holt, L. (2007). Studentification and "apprentice" gentrifiers within Britain's provincial towns and cities: Extending the meaning of gentrification. *Environment and Planning A, 39*(1), 142–61. https://doi.org/10.1068/a38476

Smith, D. P., & Hubbard, P. (2014). The segregation of educated youth and dynamic geographies of studentification. *Area, 46*(1), 92–100. https://doi.org/10.1111/area.12054

Smith, D. P., Sage, J., & Balsdon, S. (2014). The geographies of studentification: Here, there and everywhere. *Geography, 99*(3), 116–27. https://doi.org/10.1080/00167487.2014.12094405

Smith, D.P. (2004). 'Studentification': The gentrification factory? In R. Atkinson & G. Bridge (eds.) Gentrification in a Global Context: The New Urban Colonialism. Routledge. pp. 72–89.

TUIK (2024). *Demographic Features*. Retrieved July 10, 2024, from https://data.tuik.gov.tr/Kategori/GetKategori?p=Nufus-ve-Demografi-109

Tuncer, T., & İslam, T. (2017). Studentification as a new form of gentrification: Changing intra-neighborhood dynamics in Bosna-Hersek Neighborhood (Konya) [Yeni bir soylulaştırma formu olarak öğrencileştirme (Studentification): Bosna-Hersek Mahallesi'nde (Konya) değişen mahalle içi dinamikler]. *Planlama, 27*(3), 303–313. https://doi.org/10.14744/planlama.2017.77698

UK Government Legislation. (2004). Housing Act 2004 (c.34). Part 2: Licensing of houses in multiple occupation. Retrieved January 18, 2024 from https://www.legislation.gov.uk/ukpga/2004/34/part/2

Wilkinson, C., & Greenhalgh, P. (2022). Exploring student housing demand, supply side and planning policy responses in a small university city: Studentification in Durham, UK. *Housing Policy Debate, 34*(5), 746–768. https://doi.org/10.1080/10511482.2022.2137379

Yokatlas. (2024). *İzmir Katip Çelebi University*. Retrieved November 10, 2024, from https://yokatlas.yok.gov.tr/lisans-univ.php?u=1057

Megaron, Vol. 21, No. 1, pp. 75–89, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.75301

Article

Physical changes and pedestrian dynamics in public space: The Beşiktaş case

Araf Öykü Türken

Department of Urban and Regional Planning, Yildiz Technical University, Istanbul, Türkiye

ARTICLE INFO

Article history
Received: 8 June 2025
Revised: 24 February 2026
Accepted: 6 March 2026

Key words:
Behavior mapping; Besiktas; pedestrian behavior; public space;urban square.

ABSTRACT

Urban squares are crucial for urban life, enhancing city attractiveness and livability; nevertheless, many in Istanbul lack pedestrian-oriented design and sufficient infrastructure. Relatedly, several projects have been implemented in urban squares to overcome these issues. However, designing urban squares leads to both improvements and controversies, reshaping not only the physical environment but also how individuals engage with public space, and understanding pre/post dynamics of interventions provides comprehensive feedback and helps municipalities to resolve further needs. This study explores the impact of spatial changes on pedestrian behavior in Besiktas Barbaros Square (Istanbul/Turkey) and its surroundings. With a three-stage methodology, this research first identifies physical transformations by analyzing satellite imagery, street views, and field studies. Second, pedestrian flows and stationary activities are observed via manual video recordings (10 minutes, weekday/weekend, 2022-2024), capturing the site both before (once the steel overpass was removed and before the site was redeveloped) and after interventions. These observations are mapped and analyzed using QGIS. Third, perspectives from professionals (n=31) in spatial fields -urban planners, architects, and landscape architects- are gathered through surveys and open-ended responses. The findings focused on the eastern part of the square due to observational constraints, which reveal that adding urban furniture impacts dynamic/stationary activities and enhanced social interactions. The new eagle sculpture also emerged as a focal point. According to professionals' evaluations, interventions contributed to partial improvements in several aspects between pedestrians and the space. However, considering location-based potentials, green space use and the spatial connection with the urban coastline still need to be improved.

Cite this article as: Türken, A. Ö. (2026). Physical changes and pedestrian dynamics in public space: The Beşiktaş case. Megaron, 21(1):75–89.

*Corresponding author
*E-mail adress: aturken@yildiz.edu.tr

INTRODUCTION

Public spaces and urban squares are critical terms that significantly impact urban vitality, quality of life, and human behavior, so numerous discussions have been conducted on these topics. Especially after the 60s, well-known experts in urban planning, such as Jacobs (1961), Whyte (1980), and Gehl (2007; 2010; 2011) highlighted its importance in urbanized environments, and they expressed different perspectives through civic and political, or behavioral approaches related to human behavior and public space usage. Accordingly, public spaces and urban squares, as important representatives, are the beating heart of the city, and all of them have their own dynamics due to their historical background, functions, activities, and the possible encounters they create.

Relatedly, Beşiktaş Barbaros Square and its surroundings are unique spaces used not only by local communities but also by residents from across Istanbul; however, despite their historical background, locational dynamics, coastal views, and functional uses, they did not offer a human-friendly environment for many years (IMM, n.d), and created a chaotic image for users' perception based on its visual appearance, infrastructural inadequacies, limited pedestrian activities etc. (Yeşil İstanbul, 2024). With the Besiktas Square Landscaping Project -as called by the design office-, a large-scale public space transformation was launched under the initiation of Istanbul Metropolitan Municipality (IMM) and BİMTAŞ and designed by the architectural office CM Architecture (CM Architecture, 2020). As defined by the local government and the design office, the project objectives include enhancing pedestrian circulation, improving pedestrian-vehicle interaction, integrating monumental structures and squares as a part of the urban image, improving coastal relations of squares, and so on (IMM 2023; Türkay 2024; Cansız 2025). As can be seen in the upper statements, different actors may use other names to define the square. For instance, the designer office prefers the "Besiktas Square" term as well as local architectural news (Cansız, 2025; Mimarizm, 2023); whereas Çınar et al. (2021) and Zafer & Erdönmez (2021) use the "Besiktas Pier Square" in their academic studies. However, during the presentation of its project, the IMM described the area between the Besiktas pier and Besiktas Avenue as Besiktas Barbaros Square (IMM, n.d.; Yeşil İstanbul, 2024). On their website, they defined the interventions proposed for the coastal front within the framework of 'the separate yet interrelated redesign of the squares' (Barbaros Hayrettin Pasha Square and Besiktas Barbaros Square). Accordingly, this study adheres to the terminology used by the IMM.

In line with this, this research aims to understand the spatial and behavioral patterns that changed with physical interventions in the urban square. It explores the analysis of professional insights on the implemented project to identify the future requirements of the space. In terms of temporal aspects, this study has identified three stages: The pre-project stage, dominated by the steel overpass (before 2021); the transition stage, after the removal of the overpass but before the completion of the landscaping (2022–2023); and the post-project stage, after the implementation phases of the new design (2024–2025). Based on these objectives, this paper seeks to answer the following questions:

RQ1: How have contemporary spatial changes in Besiktas Barbaros Square and its surroundings influenced their public space functions and pedestrian dynamics?

RQ2: How have pedestrian behaviors and activity patterns evolved between 2022 and 2024, considering removing the steel overpass, adding urban furniture, and landscape design?

RQ3: How do urban planning and design professionals evaluate the spatial changes in Besiktas Barbaros Square and its surroundings regarding accessibility, social interaction, and pedestrian experience?

REVISITING PUBLIC SPACE DESIGN: GLOBAL APPROACHES AND LOCAL CHALLENGES ON BESIKTAS BARBAROS SQUARE

Global Approaches to Public Space Design and Evaluation Process

The city has always been a space of connection between people and functions. The '60s was a turning point for urban planning studies that focused on public space and public life, with the impact of Jacobs's (1961) famous book The Death and Life of Great American Cities; subsequently, Appleyard's (1980) ideas about livable streets and Whyte (1980) observatory studies related to social life and urban open spaces, as well as Gehl's public space and public life understanding. They all open new perspectives regarding urban design and give essential proofs and empirical arguments to future planners to show what matters in human-centric spatial design in terms of the outdoors. As one of them, Gehl's (2011) outdoor activity classification creates a systematic coding approach for behavioral research; in that study, necessary, optional, and social activities and their relation with the quality of the environment are defined in his book "Life Between Buildings (1971)". In general, necessary activities [waiting for someone, shopping, going to school/work/bus stop (primarily utilitarian walking)] cover daily tasks and are less related to exterior environments; they are conducted in almost all conditions, while optional activities are more related to favorable conditions both in terms of weather and environment. Notably, the quality of the physical environment is a significant factor for optional activities (Gehl, 2011). Relatedly, urban squares serve as meeting points that host a range of necessary, optional, and social activities, bringing people together for various purposes (Acar et al., 2021).

Since 1975, Project for Public Spaces (PPS), an interdisciplinary team, has also tried to understand parameters that make a place great through four main categories: "Sociability, uses & activities, access & linkages, comfort & image", and still conducting several works related to placemaking (PPS, 1975). Based on the principles of urban squares highlighted by PPS (2005), successful urban squares include the following features: They are an important part of the formation of image and identity in cities; they include various attractions (such as outdoor cafes, bandshell performances, etc.); they have amenities (such as lighting, benches, pathways, etc.) that enhance people's use and comfort. Squares with flexible designs (movable chairs, tables, umbrellas) are more capable of responding to different times of day/month, and spatial uses must be supported through seasonal strategies. A successful square should be easily accessible; approaches such as active outer squares and inner squares can boost accessibility and use of the square. Accordingly, good squares begin a block away, are visible, and should have entrances and support pedestrian safety. In addition, the management of good squares oversees the processes of comfort, safety, and maintenance (PPS, 2005).

During the 80s, Whyte (1980) conducted a comprehensive observational study to understand socio-spatial dynamics in small urban open spaces, such as human-human interaction, sitting spaces, wind-water-urban space relation, what is desirable in an outdoor environment, and so on, which also became a guideline for people who have studied public spaces for decades, and highlighted that people attract people. Also, Gehl (2011, p. 62) noted that physical arrangements are an essential way to promote contact in public space; for instance, no walls, short distances, low speeds, one level, and face-to-face orientations can support visual and auditory connections. Relatedly, as Andersson (2016, p. 5) highlights, there are several reasons for local governments to invest in better public spaces, such as improving the quality of life, which contributes to a sense of civic cohesion, enhancing safety in the city, and enhancing well-being, mobility, and public health.

Methodologically, observation is one of the most prevalent tools for studying public space. Techniques such as counting, mapping, tracking, photographing, and test walks—outlined by Gehl & Svarre (2013) — can be used alone or in combination. Also, questionnaire surveys, interviews, and trip diaries contribute to resolving human behaviors by capturing data about individual habits, preferences, intentions, etc. (Millonig & Gartner, 2008). Lately, technological developments have also supported the analysis of human behavior in public spaces, and new techniques and tools have automated processes, increased accuracy, and handled large amounts of data (Hanzl & Ledwon, 2017; Millonig & Gartner, 2008). As a widely used spatial representation method, behavior maps are important visual tools to present behavior data; they can be used for marking and recording behaviors or trajectories, and they may involve information about duration, activity types, traces, etc. Time-lapse videos and GIS techniques have also come to the fore in space-time behavior research (X. Zhang et al., 2021). Accordingly, several studies use these approaches with different data sources to reveal activities, cumulations, and social interactions in public spaces. As seen in the work of Marušić (2011), who combines GIS and behavioral mapping techniques to illustrate the relationships between the physical characteristics of open space and usage types, he conducted his research in two European cities, identifying occupancies, contacts, and buffer zones in urban parks. On the other hand, Petrtýlová & Jaššo (2022) use behavior mapping to analyze public space (activities, proportion of gender, space distribution, and age groups) before making decisions about its development in the waterfront of Bratislava. As another example, Ceccarelli et al. (2023) use deep learning techniques with video analytics to understand changing behavior patterns due to the intervention of street experiments during this research observation process designed for both pre- and post-intervention.

Building upon these methodological developments and theoretical frameworks, several approaches for evaluating public spaces such as streets, urban squares, etc. have been proposed. These approaches focus on understanding how the spatial organization of public space influences user experiences, activities, and pedestrians' behavioral patterns, providing critical feedback for future design practices. Therefore, measuring an urban square's spatial or behavioral performance, understanding user satisfaction, and bringing practices and design requirements are critical aims of this kind of research. Accordingly, various researchers use public space evaluation techniques to understand users' behaviors/activities or satisfaction in their research (Gong et al., 2025; Kim et al., 2018; Ozbil Torun et al., 2020; B. Zhang et al., 2023; Y. Zhang, 2017; Zhu et al., 2011). For instance, Ozbil Torun et al. (2020) evaluated urban squares in the peripheral zones of Istanbul, incorporating behavioral mapping, direct observation, user questionnaires, space syntax, and spatial analyses. Gong et al. (2025) examined usage patterns through semi-structured interviews and public features and developed age-friendly renovation strategies for residential communities in Hangzhou. Zhu et al. (2011) defined post-occupancy analyses for public space under three main categories—descriptive, evaluative, and diagnostic—and, utilizing user feedback and observation, proposed transformation strategies for the Hubin Block in Hangzhou. Maisel et al. (2021) also assessed user perceptions regarding the before-and-after conditions of a project carried out along a main street corridor. Collectively, these contributions define how public spaces can be evaluated in terms of spatial quality and user experience. While some focus on specific public spaces, others concentrate on the pre- and post-intervention. In any case, they all provide a methodological toolbox for public space studies, which also informs the three-step framework adopted in this study.

Local Constraints in Besiktas Barbaros Square and Its Surroundings

The historical background of the settlements in Besiktas dates back to permissions given to Ottoman captains, especially Barbaros Hayrettin Pasha, who became an essential figure for the zone; in the following period with the impact of movements of the palace boosted population in and around the area (Çağlayan, 2020), it turns out an essential attraction point for the Istanbul (Abay, 2021). During the Early Republican Period, several interventions were defined in the Prost plan. These include the creation of avenues and squares, the expansion of roads, the rearrangements of greenery, and monumental approaches that highlight Republican symbolism in the urban space. In the following time, relatedly to the field, the transformation process began on the coastal side of the city, and this progress also led to the design of Besiktas Square for ceremonial purposes (Çınar et al., 2021; Üresin, 2019). During the 50s, with the opening of Barbaros Boulevard, the district started to evolve into a more commercial zone (Abay, 2021), and some of the politics and transformative decisions with "Menderes operations" ended up changing the urban space (Giray Küçük, 2020). In general, green spaces decreased in time, and built-environment values (such as the Astro Tobacco Factory) in the area and surroundings that could support the cultural and coastal character of the city were lost at a certain level (Abay, 2021). At a later stage, the steel overpass constructed in the northern part of the square created a vehicle-oriented atmosphere that obstructed the square's visual potential and dominated the area's overall appearance. The impacts of the overpass and related uses in the square are detailed in the pre-project stage and serve as an important reference point for understanding subsequent spatial changes.

Since the 1990s, the Besiktas Square Project proposals have been a topic on the agenda to prioritize pedestrian use of the square and coastal side, and these issues are discussed periodically (Giray Küçük, 2020). Relatedly, the case study area -Besiktas Barbaros Square (Figure 1)- corresponds to the section located between Besiktas Pier and Besiktas Avenue. The site is associated with several registered and monumental structures, including Sinan Pasha Mosque, the Tomb of Barbaros Hayreddin Pasha, etc. (Cansız, 2025). In addition to the historical context, coastal, and transportation dynamics, another prominent dynamic related to the square is its significance as a key spot for skateboarders. This is highlighted in the article titled Skateboarding and Istanbul, where Turkey's national skateboarding team coach, Koçal, states: "Besiktas Barbaros Square is international. If a skateboarder truly lives the culture, the first place they go when visiting another country is that place's skate spot. In Istanbul, that place is Besiktas Square." (Abayhan, 2023).

Although numerous academic studies have been conducted on Besiktas Barbaros Square, to the best of the author's knowledge, no scientific research systematically examines behavioral changes related to the post-2021 transformation; however, previous studies offer valuable insights into the square's long-standing spatial dynamics. All of these studies discuss conditions before the overpass was removed and before the recent landscaping project. For instance, Zafer & Erdönmez (2021) evaluated the spatial quality of the square and mentioned that the primary usage characteristic comes from transit users. Even though space gives people some opportunities to socialize, it has evolved around public transportation and transit use instead of being pedestri-

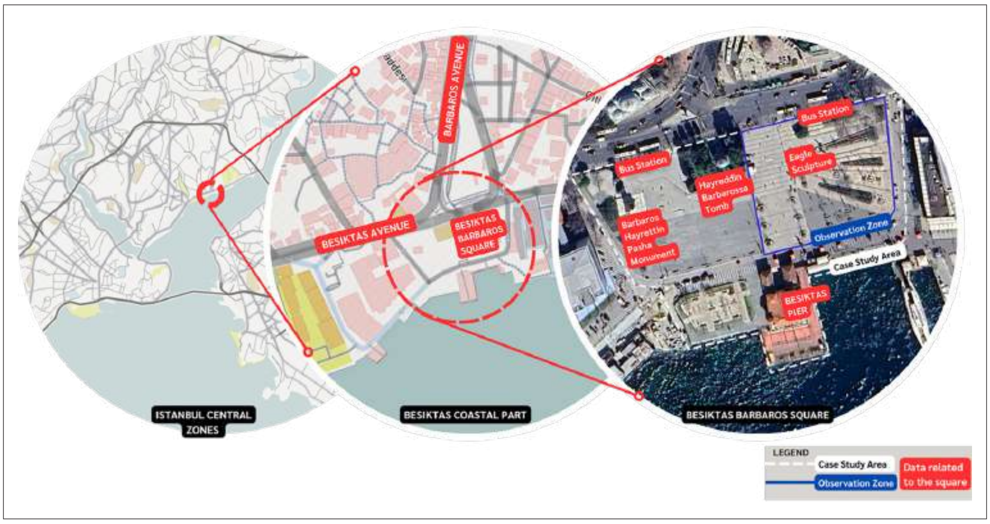

Figure 1. Location of case study area.

an-oriented, and coastal interaction is limited due to bus and ferry stops. Similarly, other scholars are also interested in the spatial quality of public spaces in Besiktas, and they address that urban equipment is insufficient, safety and perception of the square are inadequate, and the square is not accessible for disadvantaged groups (Uskan Demir et al., 2021). Çinar et al., (2021, p. 381) scored the spatial quality of the square and addressed the insufficiency of the recreation area and the need for revision of the square to highlight symbols and triangulation points to make it more memorable and distinctive. Also, Abay (2021) examined ideas related to the square, such as the urban design competition (1990) and municipal project (2007), and the project proposed in 2015. Üresin (2019) emphasized the reproduction of cities through spatial transformation and sampling this through Besiktas, and Özer & Kubat (2014) stated that the movement distribution in the Besiktas center is circular, and highlighted that there are numerous factors influencing pedestrian mobility, such as the bus stop in the southern part of Barbaros Boulevard, the main bus stop on the seaside, and the area around the pier. Considered collectively, these earlier contributions portray a square that is structurally important for mobility but qualitatively weak as a pedestrian-oriented place – a condition that the interventions explicitly set out to change. This lets the current study position itself as a follow-up that captures the latest phase of transformation.

METHODOLOGY

This research focuses on recent spatial changes in Besiktas Barbaros Square and its surroundings to provide an evidence-based examination of how pedestrians are affected by these changes and how urban professionals assess them. Accordingly, this study adopts a multi-layered methodological framework combining spatial, visual, and behavioral data sources based on three main steps. The three steps are designed to complement each other: (i) Spatial change analysis documents the physical transformation of the square over time; (ii) behavior mapping and pedestrian counting reveal how pedestrians move around and spend time in the square (2022-2024); and (iii) expert evaluations about these spatial interventions. First, satellite images, street view imagery, and visual data from field studies are comparatively used to detect changes in urban elements and facilities over time [the pre-project stage (before 2021); transition stage, after the removal of the overpass but before the completion of the landscaping (2022–2023); and the post-project stage (2024–2025)].

Second, pedestrian behavior is mapped based on video recordings taken from a fixed height (third floor) and identical locations in 2022 and 2024 under similar air temperatures and time frames (12:00–14:00), including weekday and weekend conditions (Figure 2). Each observation session consists of 10-minute video recordings. These recordings are analyzed to categorize pedestrian movements, standing behavior (durations / if any additional activities), and sitting behavior based on Gehl's (2011) approach. Traces of movement and spatial concentration of stationary activities are visualized, utilizing video-based tracking and QGIS tools for visualizing pedestrian coding. As a scope limitation, the pedestrian behavior analysis is restricted to the eastern section of the square—starting from the ending point of the pier-related transit axis and covering the first phase of the project—due to limitations in observation height, technical equipment, and visual obstructions. In addition, in manual pedestrian counting —especially in outdoor environments- counting accuracy may decrease depending on pedestrian volume and flow rates, resulting in under/over counting (Bauer et al., 2009; Greene-Roesel et al., 2008). To overcome this, this research uses the advantages of multiple reviews of video recordings by the author. However, errors may occur due to the number of people dispersed in the urban space and the use of perspective-based camera angles. Moreover, the 12:00–14:00 time period is limited regarding the representation of everyday uses. Considering the area's role as a central transport zone, it is likely that peak morning and evening flows will differ in volume and composition. This is therefore considered a temporal limitation of the behavioral analysis.

Figure 2. Observation systematic of case area.

Third, an online survey with supported visual documentation of a case study for spatial professionals was conducted to assess perceived changes before and after the interventions and reactions to the recent project. The survey was disseminated to expert groups through social media platforms and further shared via peer-to-peer referrals, resulting in responses from experts (n=31). Key indicators that shaped the evaluation matrix include pedestrian flow and movement, social interaction, usage of urban facilities and green space, aesthetic and spatial quality, coastal accessibility, and the relationship between pedestrians and vehicles. These indicators were selected to reflect the main categories emerging from the spatial change and behavior-mapping steps. There is no hierarchy between the criteria; this study adopts a comparative approach based on descriptive data, considering expert-based evaluations.

As an overview of this research, the integration of behavioral mapping of pre/post conditions and independent expert opinions about spatial changes of Besiktas Barbaros Square can be considered a design evaluation approach, giving designers and local government insights about what people need in this square for further interventions. However, it is important to assess user satisfaction beyond observed movement patterns; in that manner, this study is limited in its omission of direct user feedback concerning satisfaction levels. In addition, the defined observation boundaries cover only part of the overall design area, which limits the ability to comprehensively evaluate the newly introduced pedestrian routes.

THE SPATIAL AND BEHAVIORAL IMPACTS OF RECENT INTERVENTIONS

For many years, Besiktas Barbaros Square was characterized by dysfunctional uses that did not correspond to its urban significance. The high density of urban elements, spatial disorder, and the occupation of public space mainly caused these issues (IMM 2023; Yeşil İstanbul 2024). The urban square included a steel overpass that was used as a single-line parking area, as well as abandoned kiosks and a poorly maintained ornamental pool (Turkay, 2024). The implementation of the Besiktas Square Landscaping Project's first phase began in 2021. The area was pedestrianized with the recent project, covering nearly 29,000 square meters (IMM, 2023). One of the first interventions to achieve that was removing the steel overpass. Later, the bus stops were relocated to the northern part of the square, which contributed to the removal of vehicular traffic from the zone (IMM 2023; Cansız 2025).

In a published interview with Cem Sorguç, the founder of CM Architecture—the architectural office that actively took part in the project—he stated that one of the main goals of the design process was to bring order to the fragmented space. The project aimed to create a pedestrian-friendly, accessible square by softening level differences. He described the square as an 'urban ground' where people can spend time without being surrounded by built structures (Turkay, 2024). In addition, considering that skateboarders are an important part of the square's everyday flow, negotiations were conducted with skateboarders during the design process to support the creation of a 'skateable urban space'. So, the redesign process was developed through shared ideas of skateboarders, particularly regarding level transitions, and human ergonomics (Abayhan, 2023; Turkay, 2024). A contemporary eagle sculpture was designed by Prof. Dr. Bülent Çınar for the site, reflecting both the name of the neighborhood and the symbolic relation with Besiktas Gymnastics Club (Mimarizm, 2023; Turkay, 2024).

On the other hand, the project has been discussed during and after its introduction and implementation, particularly in online architecture forums. For instance, İzgi (2021) emphasized the need for a more participatory process and proposed suggestions based on architectural competition and public consultation practices. Cansız (2025), interpreted the project as an enhancement involving ground renovation, level adjustments, urban furniture, and lighting. Below, spatial and behavioral comparisons are detailed regarding the before-and-after conditions, as well as the perspectives of spatial professionals.

Spatial Change in Urban Square

In the previous chapter, the related spatial problems were defined by municipal officers and the design office. This chapter examines spatial changes in two- and three-dimensions using satellite images, street view, visual data collected during field trips, and project documentation. Starting from the pre-project condition, a detailed overview of the 2020 satellite imagery reveals that the steel overpass visually dominates the square, creating a chaotic and aesthetically unrefined appearance, particularly around the kiosks and seating units located beneath it. The bus stops contribute to confusion between vehicular and pedestrian flows. As an expected outcome, during this stage, the square is perceived primarily as a transit space for pedestrians seeking access to the waterfront or public transportation nodes. Stationary activities are confined mainly to seating areas associated with the kiosks and limited waiting behaviors.

Afterward, in 2022, satellite imagery revealed that the steel overpass and kiosques had been removed from the area. While the expanded open space allows for unobstructed pedestrian movement, the square lacks elements that encourage users to spend time or engage in activities. In the 2023 satellite imagery, the ongoing construction site in Besiktas Barbaros Square and around Barbaros Hayrettin Pasha Statue is visible; in this period, only limited parts of the square remain open to provide access to piers (Figure 3).

As stated by IMM, satellite images in 2024, the first and second parts of the intervention have been completed (IMM, 2023). The contemporary eagle sculpture has become a focal point by attracting public attention and enabling new forms of social interaction (Figure 4B). Together with the implemented landscape arrangements and newly introduced seating units, the urban furniture has encouraged longer stays and stationary activities, triggering a transformation in spatial dynamics. While the western part of the pier—associated with the façade of the Naval Museum—is still under construction, the elevation adjustments around the Barbaros Hayrettin Pasha Statue have been completed. The adjacent open space, designed to host temporary events, has already begun to serve various functions (e.g., temporary bazaar– Figure 4A). The inclusion of such temporary programs strengthens the square's role in civic life, rather than merely serving as a passageway. Field observations also indicate that the intersection of the transit path-

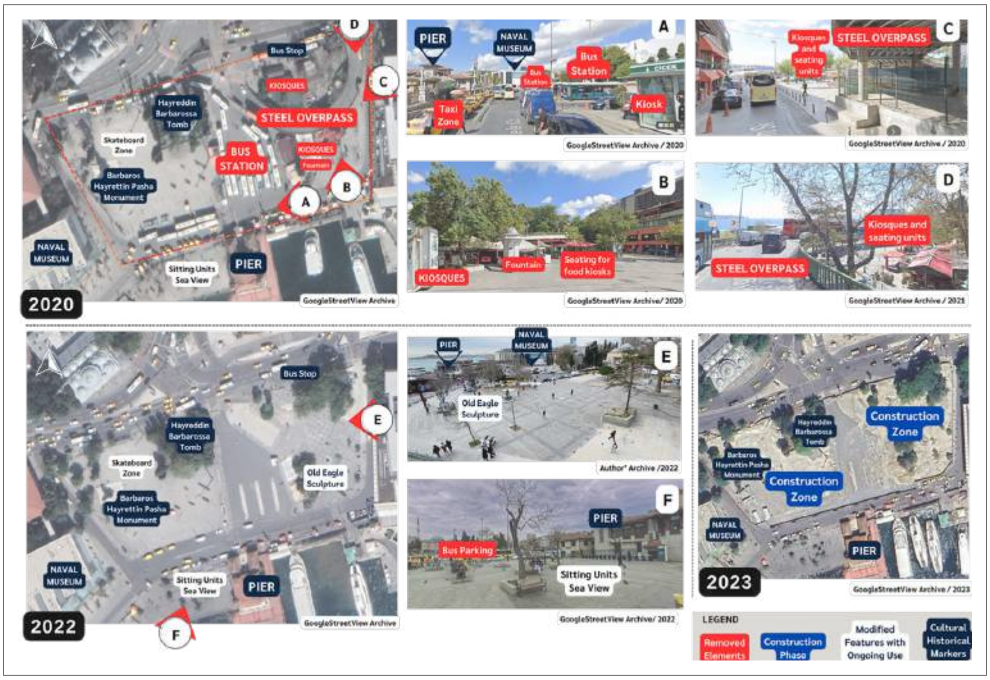

Figure 3. Pre-project conditions | Spatial changes in the urban square (2020–2022-2023).

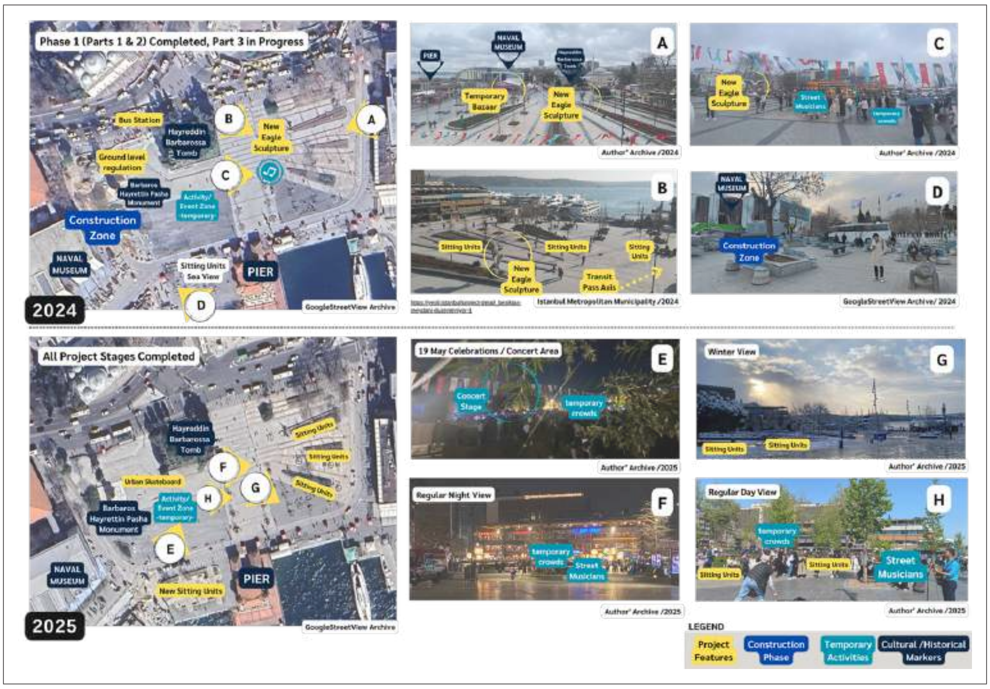

Figure 4. Post-project conditions | New dynamics in the urban square (2024-2025).

way and newly designed zones has become a performance area for street musicians, especially during noon and evening hours.

In 2025 visuals, the construction has been completed, and seasonal and time-based uses of the area—across both day and night—are detailed in Figure 4. The continued presence of street musicians has created temporary crowd formations and enhanced opportunities for spontaneous social interaction and standing activities. Additionally, changes in seasonal or event-based decorations and lighting schemes capture user attention and increase digital engagement with the square through photo and video sharing. Moreover, during festivals and public celebrations, a stage set up in front of the Barbaros Hayrettin Pasha Statue transforms the atmosphere of the square, facilitating collective urban experiences and vibrant public events that bring residents together. Accordingly, Figure 4, Image E illustrates the atmosphere of the square and event-based socio-spatial transformations observed during the Commemoration of Atatürk, Youth and Sports Day celebrations on May 19.

Video-based Pedestrian Behavior Analysis

To understand the impact of the new design project on pedestrian behavior, a total of 40-minute video analyses were conducted in a related urban square. The collected data contain comparisons of pedestrian movements in 2022 (transition stage) and 2024 (post-project stage): 2022 Represents the period following the removal of the steel overpass but prior to the initiation of landscaping; 2024 corresponds to the phase after the completion of the project's first stage and the subsequent changes in spatial use.

Accordingly, the related pedestrian counts are detailed in the graph above (Figure 5). In line with the literature and as an expected outcome, weekend usage remained higher than weekdays both in the transition phase and post-project conditions. Under the post-project condition in 2024, the decrease in weekday user numbers may be associated with light rain weather conditions or the relocation of the bus station in the urban square. Following the project implementation, a notable increase in stationary standing activities was observed on weekends. The observed decrease in sitting activities on weekday(2024) is likely related to the observation time and seasonal conditions. As shown in the upper section presenting satellite imagery and street-level views, the provided sitting units exhibit a good amount of use during peak hours and under favorable seasonal conditions (Figure 4F-4H).

As illustrated in the related maps (Figure 6), the physical space and landscape element changes between 2022 and 2024 directly influenced pedestrian flows and the locations of stationary activities. In particular, the open space configuration in 2022 facilitated diagonal crossings and concentrated stationary activities along the edge locations of the square and corners. In contrast, in line with the post-project conditions in 2024, the general pedestrian flow was shaped by landscape design, including the addition of

	Walking	Standing	Sitting
Weekday'22 /pre-project	173	17	2
Weekday'24 /post-project	127	11	1
Weekend'22 /pre-project	245	13	0
Weekend'24 /post-project	252	27	5

Figure 5. Pedestrian counts based on video recordings.

Figure 6. Behavior mappings based on video recordings.

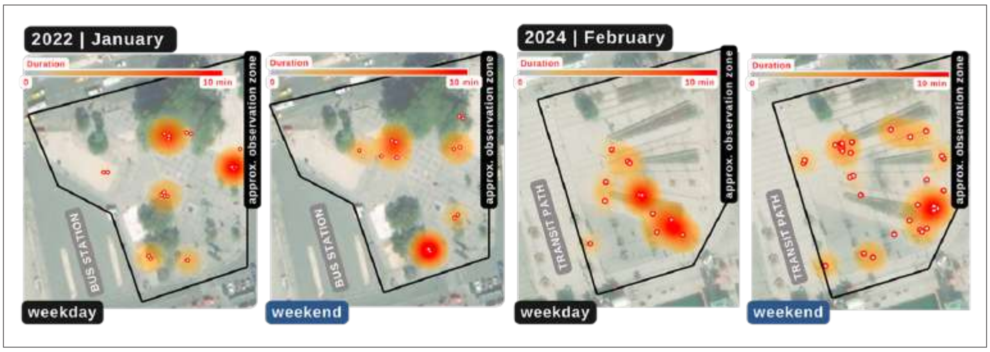

Figure 7. Stationary behavior location-choices & durations.

seating units, landscape elements, and the distribution area along the coastline to ferry/boat lines. Redesigned square contributed to a more defined and readable spatial organization compared to the spatially open yet undefined transition condition observed in 2022. While stationary and social-use patterns became more structured, pedestrians seeking rapid access to transportation corridors continued to follow desire lines, indicating that certain movement behaviors remain driven by functional needs rather than design alone. In general, in both cases, transit pedestrians tend to choose the shortest route and make diagonal crossings in the space based on their intended pier destination. On the other hand, pedestrians engaged in waiting activities have been observed to exhibit circular or exploratory behaviors in the form of circling or gazing around.

On weekends in 2024, the number of stationary activities (n=32) more than doubled compared to 2022 (n=13). While in 2022, due to the lack of dedicated seating elements, sitting activities were mainly concentrated on the stairs located under the trees (2022 total sitting count=2), in 2024, the newly introduced seating units provided through spatial design were actively used for sitting (2024 total sitting=6). Meanwhile, standing activities in 2024-post project conditions were positioned concerning the location of seating elements, landscape features, and specific focal points such as the newly installed sculpture. As illustrated in the heatmaps, medium, and long-duration activities became more prevalent in 2024 (Figure 7).

In the 2022 recordings, the most common external activities were gazing, meeting, and talking or socializing, and these activities continued under the 2024 post-project condition (Table 1). However, it was observed that the newly designed Eagle Sculpture created a significant new focal point in the post-project setting, increasing stationary activities while encouraging social and digital interactions. These interactions include taking photos with smartphones, creating new figures and urban experiences in public spaces (Argin et al., 2020). Notably, 11 people were directly observed approaching the sculpture, taking photos, or circling around it. Additionally, due to its role as a visual focal point and in line with the "people attract people" principle (Whyte, 1980), it was found that those taking photos around the sculpture encouraged others to do the same. This can be interpreted as further evidence that the new landmark supports follow-up actions. Furthermore, functional elements such as the visibly placed trash bins also supported their intended use in alignment with the square, and support daily activities. Finally, under the post-project condition, particularly during evening hours, street performers' presence influenced spatial occupation patterns, leading to larger crowd gatherings and an increase in stationary activities.

Insights from Spatial Professionals

As the third step of this research, an online survey was conducted to collect spatial professionals' opinions on the new square design and pedestrian experiences. The survey was

Table 1. Associated actions during stationary activities

	2022 | Associated actions during stationary activities	**2024 | Associated actions during stationary activities**
Social and interactive activities	gazing at or circling around (6) meeting someone (5) talking and socializing (4)	looking/ photographing the sculpture (11) gazing at or circling around (6) meeting someone (2) taking photographs (1)
Daily and functional activities	eating (2) feeding birds (1)	using a trash bin (3) eating (2) smoking (1) filling water (1) repairing a bike (1)

shared via online platforms, and responses were received from 31 spatial professionals. Among the participants [woman (n=23), man (n=8)], the age distribution was as follows: 18–24 (n=2), 25–34 (n=23), 35–44 (n=4), and 45–54 (n=2). Nineteen professionals were urban planners, eight were architects, two were landscape architects, and two participants directly identified their area of expertise as urban design. Most of participants (n=14) have been actively working in the field for 6–10 years. All experts had visited Besiktas Barbaros Square, and the majority (n=21) stated that it is a location they frequently visit. Most of them (n=19) indicated that they had followed the design and implementation process; only one expert reported not being aware of the spatial transformation process on the square (Figure 8).

In the next section of the survey, professionals were shown visual perspectives from the square: The 2020 state before the removal of bus stops and the steel overpass; the 2021 state after the steel overpass removal and prior to landscape planning; and images after the completion of the first and second phases of the project (2024). Based on these images and their personal experience, professionals were asked to evaluate and compare the old and new states of Besiktas Barbaros Square in terms of pedestrian movement and flow, potential for social interaction, urban facilities and related activities, aesthetic and spatial quality, green space usage, vehicle-pedestrian interaction, and coastal relation. Professionals, in general, indicated partial improvements in many aspects considering the before/after situations of square, as shown in Figure 9. Lastly, experts were asked to provide an overall evaluation of the square design on a scale of 1 to 5. The average score was 3.66, and the most of professionals (n=18) rated the developments in the square as 4 out of 5. However, considering green space usage and coastal relations, most professionals reported no significant improvement.

In the final part of the survey, in addition to the quantitative evaluations, open-ended responses provided by spatial professionals were systematically analyzed through content analysis. The main themes, sub-themes, and their occurrence frequencies are summarized in Table 2. As a general overview, it was detected that coastal usage, the need for shading elements, and limited greenery were criticisms. Social interaction, the atmosphere of new design, and pedestrianization-related implementations are positive aspects that reflect spatial evaluations. Additionally, experts' emphasis on the need for strengthening the square's relationship with its surroundings is critical for experiencing historical layers and coastal relations, as well as daily spatial experience. Observations from the post-project stage reveal overcrowding in certain time zones at the bus stops along the northern edge of the square. This situation indicates that spatial requirements are not fully met, considering some waiting activities.

Integrated Findings from Spatial, Behavioral, and Expert Analyses

This section brings together the findings derived from the three-stage methodological framework, structuring the results around the transformation phases of the space. Within this scope, the impacts produced by spatial interventions in Besiktas Barbaros Square are presented through intersecting outcomes across different methodological approaches.

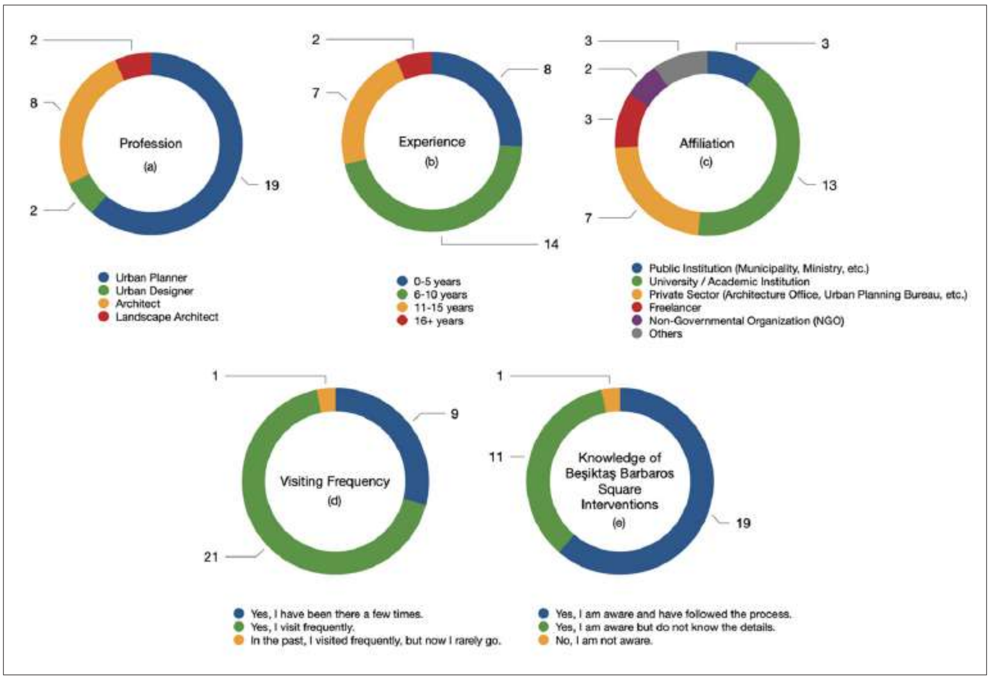

Figure 8. Spatial professionals' **(a)** profession **(b)** experience **(c)** affiliation **(d)** visiting frequency **(e)** knowledge about Besiktas Barbaros Square's redesign process.

This situation is related to the inherent complexity of researching public spaces, where relying on a single tool is often insufficient, making it necessary to combine various types of investigation (Gehl & Svarre, 2013).

Considering the observation area, aerial photographs of the pre-project stage prove that the space was dominated by the overpass structure and served primarily for transit users. Based on this, it is offering limited opportunities for stationary pedestrian activities. In this time zone, commercial kiosks generate visual pollution that covers a large part of the eastern area of the square. This finding is consistent with previous studies on the square's transit-oriented character, its limited active use (Zafer & Erdönmez, 2021), and the reduced capacity of the public space along the coastline to create spatial comfort (Abay, 2021).

Following the removal of the overpass, the transition stage introduced a release of pedestrian mobility; however, the newly formed wide and physically undefined open space became ambiguous in terms of activity management. While satellite images clearly indicate an increase in pedestrian movement areas as spatial openness expanded, behavior mapping data from 2022 support that pedestrians largely moved across the square without a defined route, predominantly choosing the shortest paths for transit. This transformation, associated with the removal of the overpass, was also positively evaluated by experts, who described the square's atmosphere as gaining a more "open and airy" character and mentioned this improvement, "view of the sea while descending from Barbaros Boulevard." At this stage, although the vista-enhancing effects of the early interventions generate a potential attraction for users (Carr et al., 2007), the absence of clearly defined structural elements in the public space limits the spatial anchoring and location choices of standing activities (Whyte, 1980).

With the completion of the post-project stage (Phase 1,2 – 2024), construction activities within the observation area were largely finalized; only a limited part of construction works around the Barbaros Hayreddin Pasha Statue were still ongoing. At this stage, supported by satellite imagery, an increase in urban elements facilitating staying and time-spending activities became evident. The square moved beyond its former role as a transit space, supported by spontaneously emerging activities [such as street musicians and interactions forming around the sculpture as well as municipal programs (e.g., temporary markets)], and acquired a physical form that more strongly accommodates stationary interactions. These types of events are a major attraction for public spaces, and they are also a popular management approach in many urban plazas and parks, providing a form of passive engagement with the space (Carr et al., 2007). In addition, Whyte (1980) remarks that "sculpture can have strong social effects" is likewise supported by the site-specific evidence. Furthermore, the behavior maps in 2024 provide direct evidence of the changes in pedestrian flows as a result of interventions in space and a rise in stationary behavior, on weekends. Similar to findings reported by Ceccarelli et al. (2023) after interventions the increase in dwell time indicates a shift from a passage space to one of stay, accordingly, a comparable situation is observed here. Although these maps do not cover peak hours, additional on-site observations indicate a clear increase in time-spent activities, especially during evening hours when use intensifies through the combination of social activities. This condition has been positively evaluated by the related experts, who noted that "the establishment of social interaction spaces has brought the area to a much better point." Taken together, as noted in the literature, improvements in the physical quality of public spaces enhance the space's inviting character, thereby supporting a broader range of standing activities (Gehl, 2011). In addition to that, celebrations, festive and events organized in the area (e.g., temporary bazaars, 19 May celebrations) support effective place management, and help deliver the sense of joy and

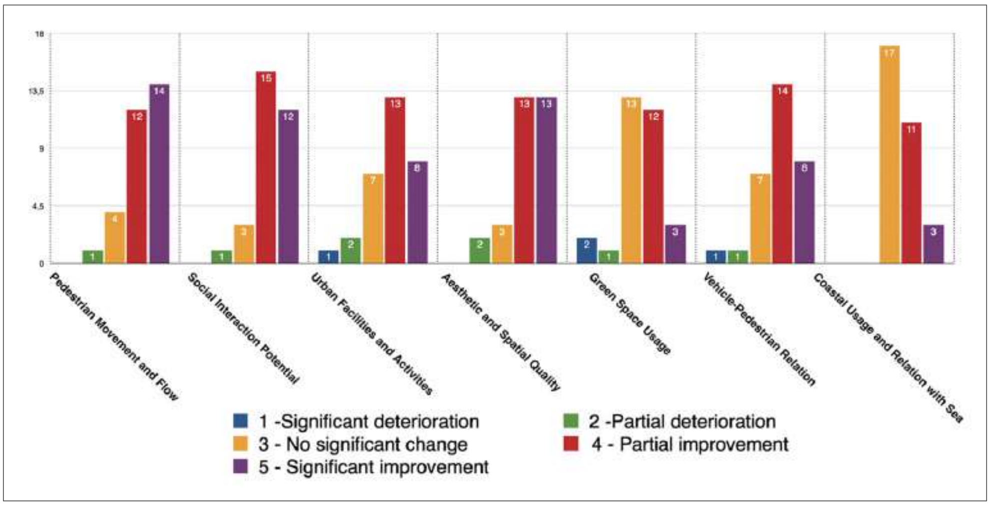

Figure 9. Spatial professionals' evaluation based on spatial-behavioral categories.

Table 2. Expert opinions on post-project spatial dynamics

Main Theme	Frequency of Theme	Sub-Themes	Selected Illustrative Statements From Participants
Coastal-Pedestrian relationship	n=10	• Limited interaction with sea and coastal use (-) • Enhancement of the sea view (+)	*"However, the parallel lines in the square design did not effectively enhance pedestrian movement or interaction with the sea and the piers. "* *"There has been no change in the use of the coastline. "* *"I think the most positive aspect of the project is the view of the sea while descending from Barbaros Boulevard. "*
Comments about new spatial design	n=9	• Enhanced Usability through Urban Furniture and Elevation Differences (+) • Pedestrian Flow and Circulation (+/-) • Insufficient Functional and Social Amenities, Stormwater Management (-)	*"The characteristic of the square being merely a transit space was partially reduced through the addition of urban furniture."* *"The elevation difference has been integrated into the design."* *"The spatial design could have been better resolved according to the primary pedestrian flow direction."* *"A design proposal considering the scale, hierarchy, material, and color compatibility with the building facades should have been developed for the square."* *"The area should be supported with functions such as food and beverage services to encourage people to spend more time there."*
Traffic/Public transportation and pedestrian-vehicle relations	n=8	• Removing the Steel Overpass (+) • Rearrangements of Bus Stops (+/-)	*"The oppressive atmosphere created by the overpass has been replaced by a more open and airy feeling."* *"Around the square, I experience problems due to congestion at the traffic lights and the crowded bus stop area for the Zincirlikuyu direction. I would have expected these issues to be successfully addressed within the scope of the project as well."*
Lack of Green Spaces and Shading Elements	n=5	• Insufficient Shading Elements (-) • Lack of Green Spaces and Trees (-) • Suggestion for further improvements (+)	*"Shading arrangements could have been made, and a greener design could have been implemented."* *"I think the biggest deficiency in the square is the lack of shading elements."* *"Although I generally find the project successful, I have concerns about the use of green spaces. Currently, I can say that the relationship between trees, their shade, and benches is quite functional, but it could be further improved."*
Integration of urban square with surroundings	n=4	• Insufficient Reflection of Historical Layers (-) • Spatial Disconnection from Surrounding Buildings (-)	*"I think the project could have improved its relationship with the Naval Museum, the surrounding piers, and the sea."* *"Traces that would reveal the historical layers of the square could have been incorporated into the design."* *"It also seems that its connection with the surrounding buildings has remained weak."*
Social interaction and pedestrian orientation	n=2	• Increase in Social Interaction Spaces (+) • Street Performers and Vibrant Atmosphere (+)	*"Street performers are using this area every evening. This really creates a pleasant atmosphere, and the seating arrangements support this design. Passing through this area in the evening is quite enjoyable."* *"Compared to a year ago, the establishment of social interaction spaces has brought the area to a much better point."*

everyday revitalization that public spaces are expected to provide (Carr et al., 2007).

Overall, expert evaluations further confirm improvements in post-intervention use patterns in terms of pedestrian movement, social interaction, urban activities, and vehicle–pedestrian relations. Nevertheless, experts also note that the rearrangement of bus stops resulted in the concentration of former transit users outside the square, reflecting management/usage-related shortcomings. In addition, insufficient functional amenities—such as food and beverage services—and inadequacies in green areas were highlighted. As Whyte (1980) notes, food vendors are a common feature of lively plazas, attracting people and supporting everyday social use, while successful squares offer diverse smaller settings—such as cafés, fountains, or sculptures—that sustain activity (PPS, 2005); therefore, in the case of Beşiktaş Barbaros Square, the introduction and strengthening of such amenities appear necessary to foster longer stays and a more diverse range of public activities. From architectural and urban planning perspectives, the new design was criticized for its weak relationship with surrounding buildings and its limited engagement with the historical layers of the site. This reflects a wider criticism of Beşiktaş Barbaros Square, given its symbolic role within the city. As has been noted in the literature, successful urban design requires a balance between aesthetic and functional aspects while protecting the city's historical, natural and cultural asset (Çınar et al., 2021).

Considering the post-project stage (2025-satellite images), during which all construction works in the Barbaros Hayreddin Pasha Statue surroundings and along the coastal line were completed, the physical interventions implemented in this phase are more micro-scale compared to those of the first and second stages. Satellite imagery states that spatial improvements were conducted in the waterfront sitting areas. Regarding experts' criticisms of overall coastal relations, it can be considered as a starting point to strengthen coast-pedestrian relations. In addition to that, on-site observations indicate the continued active use of the area by skateboarders, level adjustments between different elevations, and physical improvements in the open spaces near the statue have contributed to improving the conditions supporting skateboarding activities within the site, which aligns with the design intentions reported during the project development process (Turkay, 2024).

Taken together, the transformation of Beşiktaş Barbaros Square demonstrates that large-scale interventions alone do not encourage diverse public use. Instead, it is the spatial definition, small-scale design, and programmed/spontaneous activities that are crucial to sustaining the square's vibrancy.

CONCLUSION

This research examined spatial-behavioral patterns in Besiktas Barbaros Square and its surroundings, a well-known urban square due to its geographic location, historical background and features, and its function as a transportation hub. It compares the pre-project, transition, and post-project phases using a multi-layered methodology, providing findings that offer insights into how physical changes affect pedestrian dynamics and public space functionality.

Overall, with the removal of the steel overpass, bus stops and the implementation of pedestrianization, the square moved away from its former transit-dominated character and began to function as an open public ground (RQ1); yet, the creation of openness by itself was not sufficient; without supporting design decisions, maintenance, and seasonal programming (Gehl, 2011; PPS, 2005). In this regard, the temporary events and interaction opportunities observed in the post-project stage appear critical for activating the space and encouraging repeated use. Observations from 2022 and 2024 showed that the new spatial arrangement and the addition of iconic elements changed how pedestrians move through and use the square. These supported triangulation (Whyte, 1980) and hybrid interactions (Argin et al., 2020). Expert assessments point to various partial improvements but also to remaining gaps in the square's wider urban and coastal integration, such as new density-related pressures around revised bus stops (RQ3). These results suggest that post-project evaluation is essential for tracing how design intentions translate into everyday use. These evaluations reveal differences between designers' potential environment and users' effective environment (Marušić, 2011), and long-term monitoring is crucial for assessing the performance of interventions (Ceccarelli et al., 2023).

Beyond the specific case of Beşiktaş Barbaros Square, the findings contribute to broader debates on the relationship between pedestrian spaces, their spatial requirements and usage patterns, and everyday public life. In line with Whyte (1980) and Gehl (2010, 2011) public use must be supported by edges, objects, and activity-supporting micro-settings that encourage staying. Similarly, PPS (2005), and Carr et al. (2007) emphasize that successful squares depend on the interaction between physical design, programming, and management, a pattern also observed here as temporary events, celebrations and urban elements began to anchor stationary use. Also, collective practices historically associated with Turkish urban squares (Acar et al., 2021). At the same time, the post-project phase needs to be reconsidered from a user-oriented perspective, especially given the criticisms of the process's limited participatory scope (İzgi, 2021) and the concerns raised by experts about how the square relates to the coastal–historic context and the new transport arrangements.

Taking into consideration the limitations of this study in terms of observational constraints, manual counting processes, and the lack of direct user satisfaction surveys, future studies can investigate long-term behavioral changes in seasonal uses, and benefit from simultaneous real-time data gathering using automated pedestrian counting processes to yield higher accuracy levels. Future studies can also use comparative approaches to transformed metropolitan squares, combined with perception-based methods, to improve our understanding of the long-term impact of spatial interventions on public spaces.

ETHICS: The questionnaire administered to spatial professionals has been approved by the Ethics Committee for Social and Human Sciences Research at Yildiz Technical University, and no ethical issues have been identified in the data collection tools and methods.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support

ACKNOWLEDGMENTS: Preliminary findings of this study were presented at the III. International Architectural Design Conference RIXARCH (Riga, Latvia) on March 27, 2025. I would like to express my sincere gratitude to the organizing committee, session chair and the audience for their valuable and constructive feedback.

AI USAGE: This manuscript benefited from AI-assisted language editing using OpenAI's ChatGPT 5.2. The author is solely responsible for the content, accuracy, and interpretations presented in the text.

REFERENCES

Abay, E. (2021). Space at the urban–coastal intersection: The case of Beşiktaş [Kent kıyı kesişiminde mekan; Beşiktaş örneği]. *JENAS Journal of Environmental and Natural Studies, 3*(3), 271–283. https://doi.org/10.53472/jenas.1024669

Abayhan, A. (2023). Istanbul and skateboarding [İstanbul ve kaykay]. *İstanbul Dergisi İBB*, 15. Retrieved January 15, 2024, from https://www.istdergi.com/sehir/spor/istanbul-ve-kaykay

Acar, H., Yavuz, A., Eroğlu, E., Acar, C., Sancar, C., & Değermenci, A. S. (2021). Analysis of activity, space and user relations in urban squares. *Indoor and Built Environment, 30*(9), 1466–1485. https://doi.org/10.1177/1420326X20942271

Andersson, C. (2016). Public space and the new urban agenda (*). *The Journal of Public Space, 1*(1), 5–10. https://doi.org/10.5204/jps.v1i1.4

Appleyard, D. (1980). Livable streets: Protected neighborhoods? *The Annals of The American Academy*, *451*, 106–117. https://doi.org/10.1177/000271628045100111

Argin, G., Pak, B., & Turkoglu, H. (2020). Between post-flâneur and smartphone zombie: Smartphone users' altering visual attention and walking behavior in public space. *ISPRS International Journal of Geo-Information, 9*(12), 700. https://doi.org/10.3390/ijgi9120700

Bauer, D., Brandle, N., Seer, S., Ray, M., & Kitazawa, K. (2009). Measurement of pedestrian movements: A comparative study on various existing systems. In *Pedestrian Behavior: Models, Data Collection and Applications* (pp. 325–344). Emerald. https://doi.org/10.1108/9781848557512-015

Çağlayan, M. (2020). A look at Beşiktaş's urban transformation in the 19th century [Beşiktaş'ın 19. yüzyıldaki kentsel dönüşümüne bir bakış]. *Artuklu İnsan ve Toplum Bilim Dergisi*, *5*, 33–52. https://doi.org/10.46628/itbhssj.707051

Cansız, A. U. (2025). Beşiktaş city square arrangement project [Beşiktaş kent meydanı düzenleme projesi]. Retrieved January 15, 2024, from https://www.arkitera.com/proje/besiktas-kent-meydani- duzenleme-projesi/

Carr, S., Francis, M., Rivlin, L. G., & Stone, A. M. (2007). Needs in Public Space. In M. Carmona & S. Tiesdell (Eds.). *Urban Design Reader*, pp. 230–241.

Ceccarelli, G., Messa, F., Gorrini, A., Presicce, D., & Choubassi, R. (2023). Deep learning video analytics for the assessment of street experiments: The case of Bologna. *Journal of Urban Mobility, 4,* 100067. https://doi.org/10.1016/j.urbmob.2023.100067

CM Architecture. (2020). Beşiktaş square landscaping project. https://cmmimarlik.com.tr/en/project/besiktas-town-square-landscaping-project/

Çınar, H. S., Kanbur, N., Çavdur, E., Dinçer, B., Özdemir, A., & Iokhim, P. (2021). Research on urban identity: Example of Beşiktaş pier square. *Bartın Orman Fakültesi Dergisi, 23*(2), 370–385. https://doi.org/10.24011/barofd.885797

Gehl, J. (2007). Public spaces for a changing public life. In C. Ward Thompson & P. Travlou (Eds.), *Open Space: People Space* (pp. 3–10).

Gehl, J. (2010). *Cities for people*. Island Press.

Gehl, J. (2011). *Life between buildings*. Island Press.

Gehl, J., & Svarre, B. (2013). *How to study public life?* Island Press. https://doi.org/10.5822/978-1-61091-525-0

Giray Küçük, S. (2020). Bosphorus coastal road and settlements between Beşiktaş and Bebek in 1939 plan. *Iconarp International Journal of Architecture and Planning, 8*, 54–80.https://doi.org/10.15320/iconarp.2020.143

Gong, M., Wang, N., Chu, Y., Wu, Y., Huang, J., & Wu, J. (2025). Optimizing public spaces for age-friendly living: Renovation strategies for 1980s residential communities in Hangzhou, China. *Buildings, 15*(2), 211. https://doi.org/10.3390/buildings15020211

Greene-Roesel, R., Diogenes, M. C., Ragland, D. R., & Lindau, L. A. (2008). Effectiveness of a commercially available automated pedestrian counting device in urban environments: Comparison with manual counts. http://escholarship.org/uc/item/2n83w1q8

Hanzl, M., & Ledwon, S. (2017). Analyses of human behaviour in public spaces. Retrieved January 15, 2024, from https://www.researchgate.net/publication/326736336

İzgi, S. (2021). Beşiktaş: Is another opportunity slipping away? [Beşiktaş: Yine bir fırsat mı kaçıyor?] Retrieved January 15, 2024, from https://www.arkitera.com/gorus/besiktas-yine-bir-firsat-mi-kaciyor/

Istanbul Metropolitan Municipality (IMM). (n.d.). Beşiktaş Barbaros square and surrounding area arrangement [Beşiktaş Barbaros meydan ve çevre düzenlemesi]. Retrieved January 15, 2024, from https://yesil.istanbul/project-detail_besiktas-meydan-ve-cevre-duzenlemesi

Istanbul Metropolitan Municipality (IMM). (2023). *Beşiktaş Barbaros meydanı*. Retrieved January 15, 2024, from https://yesil.istanbul/project-detail_besiktas-meydani-duzenleniyor-1

Jacobs, J. (1961). *The death and life of great American cities*. Vintage Books.

Kim, H. J., Chae, B. K., & Park, S. B. (2018). Exploring public space through social media: An exploratory case study on the High Line New York City. *Urban Design International, 23*(2), 69–85. https://doi.org/10.1057/s41289-017-0050-z

Maisel, J. L., Baek, S. R., & Choi, J. (2021). Evaluating users' perceptions of a Main Street corridor: Before and after a complete street project. *Journal of Transport and Health, 23*, 101276. https://doi.org/10.1016/j.jth.2021.101276

Marušić, B. G. (2011). Analysis of patterns of spatial occupancy in urban open space using behaviour maps and GIS. *Urban Design International, 16*(1), 36–50. https://doi.org/10.1057/udi.2010.20

Millonig, A., & Gartner, G. (2008). Shadowing-tracking-interviewing how to explore human spatio-temporal behaviour patterns. *BMI*, *396*, 1–14.

Mimarizm. (2023). *The first phase of Beşiktaş Square has opened* [Beşiktaş meydanı'nın ilk etabı açıldı]. Retrieved January 15, 2024, from https://www.mimarizm.com/haberler/gundem/besiktas-meydani-nin-ilk-etabi-acildi_136302

Ozbil Torun, A., Yesiltepe, D., Erten, S., Ozer, O., Gurleyen, T., & Zumbuloglu, E. (2020). Measuring the relationship between spatial configuration, diversity and user behavior: A post occupancy evaluation study in Istanbul's peripheral districts. *Journal of Design for Resilience in Architecture and Planning, 1*(1), 84–102. https://doi.org/10.47818/drarch.2020.v1i1006

Özer, Ö., & Kubat, A. S. (2014). Walkability: Perceived and measured qualities in action. *ITU AZ, 11*(2), 101–117.

Petrtýlová, R., & Jaššo, M. (2022). Behavioural mapping and online data as tools for socio-spatial analysis of public spaces—Bratislava, Slovakia waterfront case study. *GeoScape, 16*(1), 39–54. https://doi.org/10.2478/geosc-2022-0004

PPS. (1975). *Project for public space*. https://www.pps.org

Project for Public Spaces (PPS). (2005). *10 principles for successfull squares*. Retrieved January 15, 2024, from https://www.pps.org/article/squaresprinciples

Turkay, B. (2024). *Barbaros Square: The transformation process of a multi-identity center* [Barbaros meydanı: Çok kimlikli bir merkezin değişim süreci]. Retrieved January 15, 2024, from https://www.rastmagazine.com/yazilar/barbaros-meydani-cok-kimlikli-bir-merkezin-degisim-sureci-besiktas-cem-sorguc

Üresin, M. (2019). *Reproduction of cities by capital and politics and transformation of public spaces: Beşiktaş example* [Master Thesis]. Istanbul Technical University.

Uskan Demir, M., Akkurt, E., & Erdönmez, M. E. (2021). Evaluation of public spaces in Beşiktaş in terms of spatial quality. *JENAS Journal of Environmental and Natural Studies, 3*(2), 153–173.

Whyte, W. H. (1980). *The social life of small urban spaces*. PPS.

Yeşil İstanbul. (2024). Beşiktaş Barbaros Square has acquired its new form [Beşiktaş Barbaros meydanı yeni haline kavuştu] [Broadcast]. Retrieved January 15, 2024, from https://www.youtube.com/watch?v=VFpRej5-SKs

Zafer, S., & Erdönmez, E. (2021). Spatial quality research in public open spaces: The case of Beşiktaş pier square and surrounding. *Urban Academy Journal of Urban Culture and Management*, 14, 241–258. https://doi.org/10.35674/kent.866176

Zhang, B., Song, Y., Liu, D., Zeng, Z., Guo, S., Yang, Q., Wen, Y., Wang, W., & Shen, X. (2023). Descriptive and network post-occupancy evaluation of the urban public space through social media: A case study of Bryant Park, NY. *Land, 12*(7), 1403. https://doi.org/10.3390/land12071403

Zhang, X., Cheng, Z., Tang, L., & Xi, J. (2021). Research and application of space-time behavior maps: A review. *Journal of Asian Architecture and Building Engineering, 20*(5), 581–595. https://doi.org/10.1080/13467581.2020.1800473

Zhang, Y. (2017). *Post occupancy evaluation theory application in the urban park*. Retrieved January 15, 2024, from https://www.worldscientific.com/worldscibooks/10.1142/10260?srsltid=AfmBOorIPXY-PRzZSaLZB2Qa4QvO3-7vKfBC0W77I_pqs4t5d-vKBgO3DK#t=aboutBook

Zhu, X. Q., Song, S. H., & Su, Y. (2011). *Spatial POE and strategies on public place: A case study on Hubin block in Hangzhou.* Retrieved January 15, 2024, fromhttps://ieeexplore.ieee.org/document/5776159/metrics#metrics

Megaron, Vol. 21, No. 1, pp. 90–100, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.47886

Article

Comparative analysis of text-To-3D AI tools in urban furniture design: Evaluating Luma Genie, Meshy, Tripo, and DeepAI

Erdem Yıldırım, Furkan Samet Küçük

Department of Architecture, Dokuz Eylül University, Izmir, Türkiye

ARTICLE INFO

Article history
Received: 17 September 2025
Revised: 23 November 2025
Accepted: 26 March 2026

Key words:
AI-driven design; Deepai; Meshy; text-to-3D AI; Tripo; urban furniture.

ABSTRACT

This study explores the potential of text-to-3D model AIs in designing urban furniture, with a focus on bus stops, street lamps, and benches, and provides a comparative evaluation of four prominent AI tools: Luma Genie, Meshy, Tripo, and Deepai. A diverse poll of architects, urban planners, industrial designers, and students assessed the outputs based on key criteria: Aesthetic appeal, texture detail, form detail, and technical consistency and feasibility. The comparative analysis revealed that Meshy consistently outperformed the other platforms across all criteria, achieving the highest overall score of 4.09. Meshy's success is attributed to its high performance in visual creativity, structural sophistication, and spatial awareness. Conversely, Deepai lagged significantly, notably lacking in functional logic, spatial awareness, and technical consistency, resulting in the lowest overall score of 1.69. While Luma Genie and Tripo showed balanced performance, they did not match Meshy's degree of structural and aesthetic intricacy. This study highlights the current limitations of text-to-3D AI, emphasizing that platform-specific features like customization and technical control play a critical role in generating feasible architectural outputs for the future of urban design.

Cite this article as: Yıldırım, E., & Küçük, F. S. (2026). Comparative analysis of text-To-3D AI tools in urban furniture design: Evaluating Luma Genie, Meshy, Tripo, and DeepAI. Megaron, 21(1):90–100.

INTRODUCTION

Design workflows have changed dramatically with the advent of text-to-image AI technology. These models have given developers, designers, and artists new options by transforming written descriptions into intricate visual outputs. There are numerous applications for text-to-image models, including the creation of conceptual artwork and illustrations, as well as the generation of lifelike visuals for marketing and advertising (Reed, et al., 2016).

Following the success of text-to-image models, the development of text-to-3D AI technology represents the next step in AI-driven design. By creating three-dimensional structures from textual descriptions, text-to-3D models improve the functionality of 2D models. This innovation creates new prospects mainly in gaming (Li, et al., 2024a; Lindfors, 2025; Vimpari, et al., 2023), architecture (Ko, et al., 2023; Öcal, et al., 2024; Zhuang, et al., 2023), extended reality (Behravan, 2025; Lee, et al., 2024; Sahebnasi, et al., 2024; Yeo, et al., 2023), industrial design (Althi, et al., 2023; Deng, et al., 2024a; Edwards, et al., 2024), and mechanical engineering (Šarčević, et al., 2024; Yavartanoo, et al., 2024). To create complex 3D objects, these AI models primarily utilise neural networks, which enable designers to visualise

***Corresponding author**
*E-mail adress: erdem.yildirim@deu.edu.tr

and refine their ideas more quickly (Cai, 2023; Deng, et al., 2024b; Shen, et al., 2024).

There are several challenges when using text-to-3D AI in urban planning. Despite the fact that these models have shown promise in producing specific objects, such as characters (Fu, et al., 2023), household items (Behravan, et al., 2025), or furniture (Bier, et al., 2024; Fang, et al., 2025), they have not yet attained comparable success in the broader context of urban planning and design (Fallacara, et al., 2023). The intricacy of urban settings, characterized by complicated spatial relationships and varied functional demands, presents considerable challenges for AI models (Lu, et al., 2024). Notwithstanding these obstacles, there are few instances of text-to-3D AI effectively generating unique and functional furniture designs (Cordero, et al., 2025; Z. Li,, et al., 2024b; Zeyin, et al., 2024). These examples illustrate AI's capacity to enhance furniture design, specifically for individual artifacts rather than comprehensive metropolitan environments, for now.

This research aims to examine the functionalities of text-to-3D AI models in the design of urban furniture, focusing on elements of bus stops and their associated amenities, including benches, billboards, and photovoltaic panels. Our research aims to evaluate four prominent AI platforms -Luma Genie, Meshy, Tripo, and DeepAI- to assess their potential for creating innovative and functional urban furniture. We propose that among the platforms we evaluated, those offering the highest levels of customization and visual complexity, specifically Meshy AI and Luma Genie, will stand out in terms of aesthetic appeal and detailed forms. However, we also anticipate that maintaining technical consistency will remain a significant challenge for all platforms when handling complex urban design prompts.

LITERATURE REVIEW

Synopsis of Text-to-3D AI Technology

The emergence of text-to-3D artificial intelligence has opened up new avenues in generative design workflows, particularly for non-expert users seeking to create functional or expressive 3D content. As the field continues to grow, recent literature has focused on categorizing technical approaches, benchmarking system performance, and identifying application-specific limitations (Huang, et al., 2024; Kim, et al., 2024; Liu, et al., 2022; Ma, et al., 2024; H. Zhang, 2020).

One of the most comprehensive overviews is presented by Li, et al. (2023), who provide a detailed survey of text-to-3D technologies in the context of AI-generated content (AIGC). Their study categorizes methods based on 3D data representations (e.g., voxels, meshes, NeRF) and evaluates core performance metrics such as fidelity, consistency, and controllability. A broader perspective is provided by Foo, Rahmani, and Liu, who survey AI-generated content (AIGC) across multiple data modalities (Foo, et al., 2023). Furthermore, focused comparative studies in domains like mechanical design provide a useful evaluation framework centered on structural accuracy, geometric fidelity, and usability for assessing output functionality in design-oriented tasks (Buljat, 2024).

Applications in Urban Design

The incorporation of AI into urban planning has emerged as a significant focus, especially with the development of smart cities (Allam & Dhunny, 2019) and the improvement of urban living conditions (Luusua & Ylipulli, 2020). AI technology has been utilized in multiple facets of urban planning and design (Kamrowska-Załuska, 2021; Yuchen, et al., 2019), including the creation of urban furniture (Cordero, et al., 2025). A notable study investigated the application of generative design algorithms to develop urban features that adjust to varying environmental circumstances and user requirements (Sanchez, et al., 2024).

Current Comparative Analyses of AI Platforms within Design Contexts

Comparative evaluations of AI platforms in design contexts have gained significance as these technologies grow and integrate into other disciplines. These studies offer critical insights into the advantages and disadvantages of various AI tools, assisting designers and researchers in making educated choices regarding the appropriate platforms for certain applications.

A significant study performed a comparative comparison of analogical and machine learning methodologies in urban design research (Brisotto, et al., 2023). This study examined the application of machine learning to find urban indicators of citizens' well-being, contrasting it with conventional analogical methods. A notable comparative study examined the convergence of ergonomics, design thinking, and artificial intelligence/machine learning in design innovation (Leão, et al., 2024). A research in instructional design assessed the efficacy of different AI platforms in generating multimedia content customized for particular academic disciplines (Kazanidis & Pellas, 2024).

Gap in the Literature

A notable deficiency is the insufficient emphasis on the practical execution and enduring consistency of AI-generated urban furniture designs. Although numerous studies emphasize the capacity of AI to generate novel and functional ideas, empirical information about the performance of these designs in real-world contexts over prolonged durations is lacking. Furthermore, there is a significant deficiency of comparative research that systematically assess the efficacy of various Text-to-3D AI platforms in design. Although many studies have examined AI tools within broader design frameworks, particular evaluations of platforms such as Midjourney, Dall-E or LeonardoAI concerning urban furniture are limited text-to-image algorithms (Cho, et al., 2022; Yıldırım, 2023).

METHODOLOGY

Artificial Intelligence Platforms and Their Functionalities

This research assesses four leading text-to-3D AI platforms: Luma Genie, Meshy, Tripo, and Deepai. Each platform possesses distinct qualities that render it suitable for specific aspects of urban furniture design.

- Deep AI processes the text descriptions provided by users and generates 3D models that match these descriptions. For each prompt, Deep AI produces a single model, and customizations are made solely through the prompt. It offers unlimited usage, allowing for continuous creativity without restrictions (DeepAI, 2025).
- Luma Genie: Renowned for its advanced visual imagination and structural sophistication, Luma Genie specializes in producing intricately detailed and visually sophisticated 3D models. It employs cutting-edge neural networks to analyze textual descriptions and generate robust designs. Additionally, it quickly generates 4 drafts without any cost or limit. The desired drafts can be further refined in more detail, also free of charge (Luma Labs, 2025).
- Meshy is an innovative tool that allows users to create high-quality 3D models from text-based descriptions. Meshy provides the flexibility to customize model generation by adjusting features such as Art Style, Target Polycount, Topology, and Symmetry. Upon entering a prompt, it generates four models without textures, which can then be individually textured if desired. After the model generation, any texture inaccuracies can be corrected, and animations can be added to humanoid models. With these features, Meshy offers a range of options that are particularly beneficial for game designers. It offers a monthly credit system, where credits are used for model generation and texturing operations (Meshy, 2025).
- Tripo is a specialized AI tool designed for 3D model creation and animation. Without offering customization options, Tripo generates four high-quality models with PBR texture style. Since these models are produced with textures and in high resolution, there's no need for separate texturing work. The developers have prioritized language model training, ensuring an accurate comprehension of the input prompts. Tripo AI provides users with monthly credits. These credits can be used for model generation and adding animations to the models (Tripo3d, 2025).

Research Design Outputs

The research design encompasses a sequence of design prompts centered on the design context which involves bus stop, bench, billboard, and photovoltaic panel combination.

Prompt: 'Create a 3D model of a bus stop with a futuristic, organically shaped that draws inspiration from parametric design that includes a bench, a billboard and photovoltaic panels'

Justification for Prompt Selection: The part "futuristic, organically shaped that draws inspiration from parametric design" was chosen to make the AI models create designs that test their ability to make complex, non-standard geometry and detailed forms. The complicated addition of "a bench, a billboard, and photovoltaic panels" was chosen to see if the model could combine several different types of urban furniture into one 3D model that was structurally sound.

Every AI platform was assigned the responsibility of generating designs in accordance with these instructions (Figure 1; Figure 2; Figure 3; Figure 4).

Individuals involved

A varied cohort of individuals was assembled to assess the AI-generated designs. 106 attendees comprised mainly architects, also landscape architects, interior architects, industrial designers, and students from these fields. Participants were also asked about their familiarity with text-to-3D modeling tools, categorized into three levels: 'Never heard of it', 'Heard of it but never used', and 'Heard of it and have used it'.

Assessment Standards

Evaluation Criteria

The designs were assessed using a standardized set of criteria:

- Aesthetic Appeal: Evaluates the visual attractiveness and creativity of the designs. Participants rated how visually appealing and innovative the designs were.

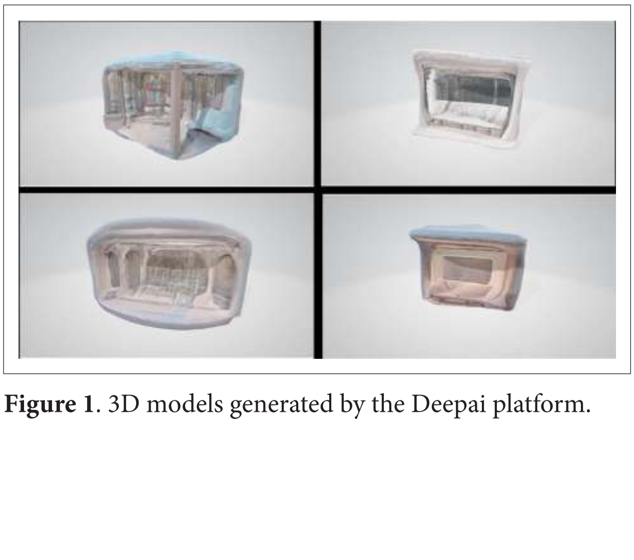

Figure 1. 3D models generated by the Deepai platform.

- Texture Detail: Assesses the quality and realism of the textures used in the designs. This criterion focuses on the detail and accuracy of the surface textures.

Figure 2. 3D models generated by the Luma Genie platform.

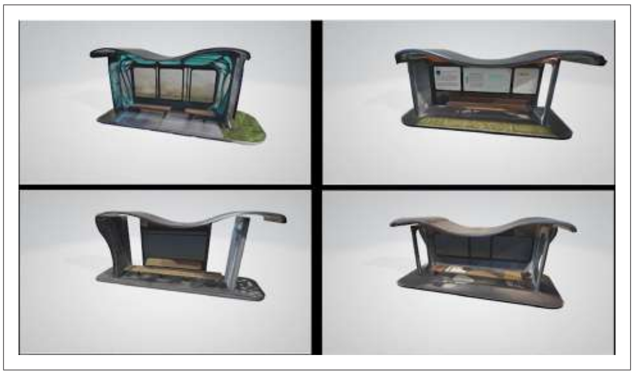

Figure 3. 3D models generated by the Meshy platform.

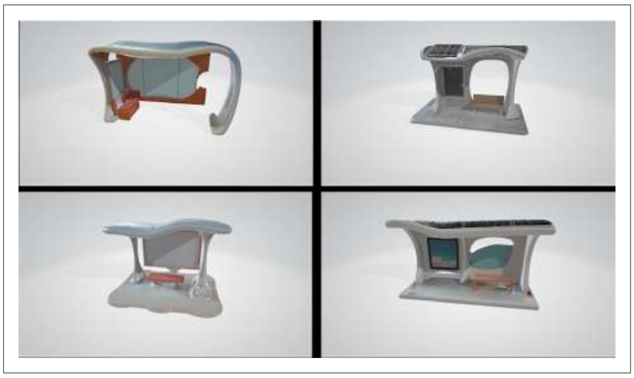

Figure 4. 3D models generated by the Tripo platform.

- Form Detail: Examines the intricacy and precision of the design forms. This includes the complexity and clarity of the shapes and structures.
- Technical Consistency and Feasibility: Evaluates the practicality and buildability of the designs. This criterion considers how well the designs can be realized in real-world applications, including structural integrity and material use.
- Overall Score: Provides a general rating based on the combined assessment of all the criteria.

This score reflects the overall quality and effectiveness of the designs.

The data collected from the evaluations were analyzed using quantitative methods. Descriptive statistics summarized the ratings, while inferential statistics, such as ANOVA, identified significant differences between the AI platforms.

RESULTS

Basic Analysis

Text-to-3D AI tools were evaluated by users based on five main criteria: Aesthetic appeal, texture detail, form detail, technical consistency and feasibility, and overall success. The analysis of average scores for each tool clearly highlighted the strengths and weaknesses of different tools (Table 1).

The aesthetic evaluation was an important criterion to measure users' visual preferences. In this category, the "T" (Meshy AI) tool scored 3.84, surpassing the other tools. The "X" (Tripo AI) tool took second place with a score of 3.34, while the "Z" (Luma Genie AI) tool showed relatively low performance with a score of 2.68. The lowest score was 1.88 for the "Y" (Deep AI) tool, indicating significant deficiencies in visual appeal.

In terms of texture detail, the Meshy AI AI tool stood out with a score of 4.00, demonstrating its success in material descriptions. The LumaAI tool ranked second in this area with a score of 3.01. In contrast, the DeepAI tool only scored 1.53, failing to meet users' expectations. This indicates that texture detailing is a significant area for improvement for the DeepAI tool.

similar ranking was observed in the form detail category. The Meshy AI tool once again led with a score of 4.13, while the LumaAI and Tripo AI tools scored 3.11 and 3.23, re-

Table 1. The scores received by AI tools based on survey results

	Aesthetics	Material detail	Form detail	Feasibility	Overall success	Total score
X (TripoAI)	3.34	3.06	3.23	3.42	3.25	16.3
Y (DeepAI)	1.88	1.53	1.84	1.93	1.69	8.87
Z (LumaAI)	2.68	3.01	3.11	3.57	3.03	15.4
T (MeshyAI)	3.84	4.0	4.13	4.08	4.09	20.14

spectively. However, the DeepAI tool had the lowest performance in this area as well, with a score of 1.84. This shows that users found the DeepAI tool inadequate in terms of geometric detailing.

In the technical consistency and feasibility criterion, the Meshy AI tool performed the best with a score of 4.08. This result indicates that the Meshy AI tool stands out not only in design quality but also in technical feasibility. The LumaAI and Tripo AI tools also performed well in this category, scoring 3.57 and 3.42, respectively. In contrast, the DeepAI tool had the lowest performance in this category as well, with a score of 1.93, highlighting its weaknesses in technical reliability.

Finally, when examining the overall success scores, the Meshy AI tool ranked first with a score of 4.09. The Tripo AI and LumaAI tools scored 3.25 and 3.03, respectively. However, the DeepAI tool only scored 1.69, indicating a very low level of user satisfaction.

In this study, to minimize biases, the names of the AI tools were not specified during the survey phase. This approach aimed to ensure that participants evaluated only the functional and experiential aspects, independent of brand or tool recognition. This method allows for a more objective interpretation of the findings and a healthier comparison of differences between the tools. The AI tools, whose names were not specified during the survey, were used to denote models prepared by TripoAI, DeepAI, LumaAI, and MeshyAI. When the scores of these AI tools across all criteria were totaled, the Meshy AI tool clearly led with a score of 20.14. This result indicates that the Meshy AI tool is the most successful in terms of aesthetics, technical aspects, and user satisfaction. Among the other tools, the Tripo AI and LumaAI tools showed balanced performance with total scores of 16.30 and 15.40, respectively, while the DeepAI tool lagged significantly with a score of 8.87. This indicates that the DeepAI tool struggles to meet user expectations.

Correlation Analysis

The correlation analysis examined the strength of the linear relationship between the five assessment criteria and the final Overall Success Score given by participants. The investigation is essential, as the correlation coefficient quantifies the direct influence of a criterion on overall success, whereas the average scores just indicate the independent magnitude of that criterion.

Figure 5 demonstrates the factors -Aesthetics, Material Detail, Form Detail, or Feasibility- that were most pivotal in shaping the final evaluation of each model.Principal Insights: Meshy AI (T): The variable Aesthetics had the most robust correlation (0.62), indicating that users emphasized the visual attractiveness of the top-rated model. DeepAI (Y): Material Detail emerged as the most significant factor (0.64), indicating that the perceived quality of materials was the principal determinant of its poor overall score. Luma Genie (Z): Aesthetics exhibited the strongest correlation (0.53), whilst Feasibility shown the least influence (0.30). Feasibility consistently exhibited the poorest link with the Overall Score for Meshy AI, Tripo AI, and Luma Genie, indicating that participants predominantly prioritized design quality (Aesthetics and Detail) over technical buildability.

A correlation analysis was conducted to examine the impact of various criteria on the overall perception of quality. The results were shown in heatmaps (Figure 6; Figure 7; Figure 8; Figure 9). The correlation coefficient is a number between -1.00 and +1.00 that shows how strong and in what direction the linear relationship is between two assessment criteria1. Values near

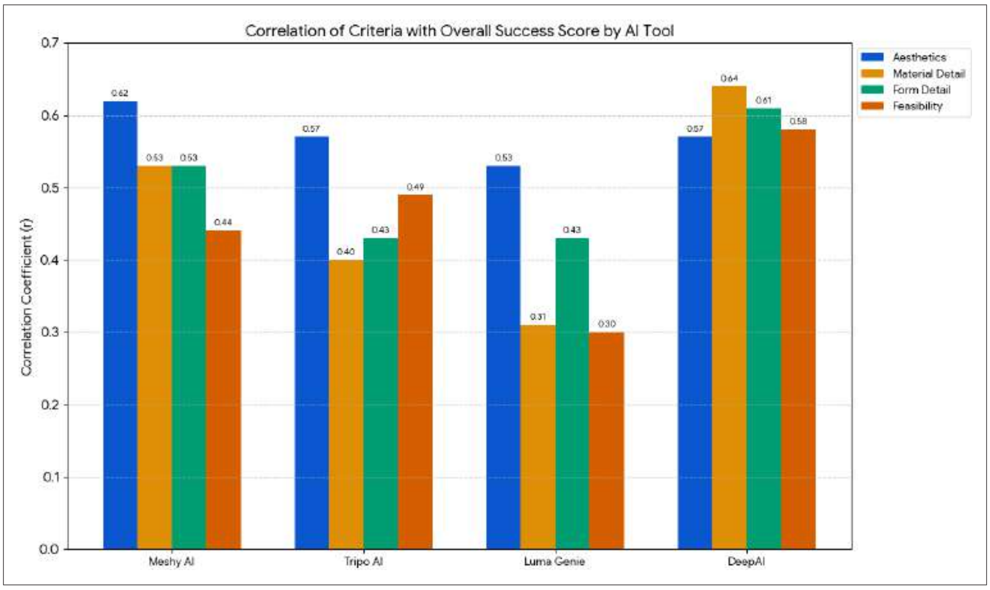

Figure 5. Correlation of criteria with overall success score by AI Tool.

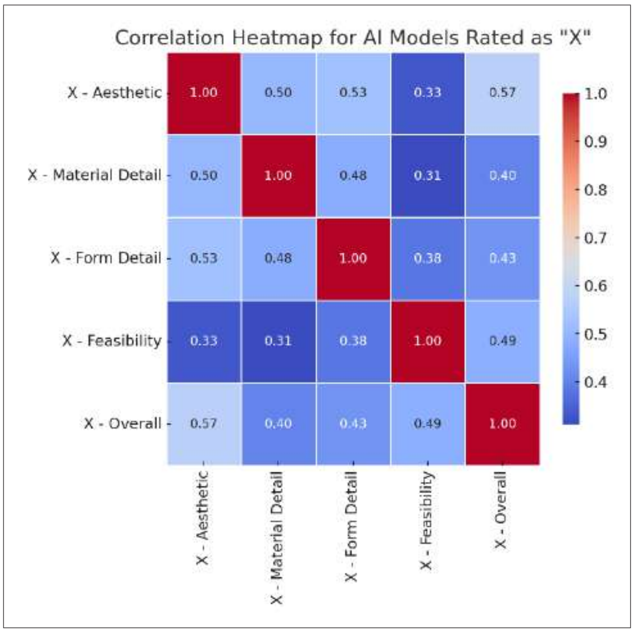

Figure 6. Correlation heatmap for Tripo AI.

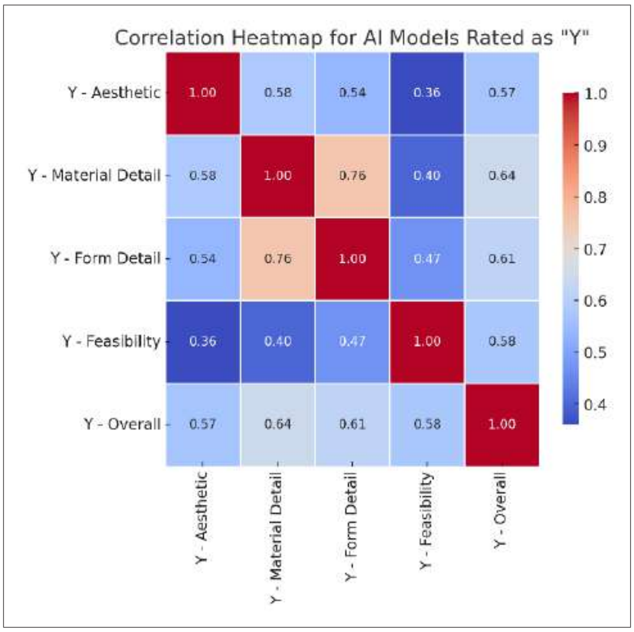

Figure 7. Correlation heatmap for DeepAI.

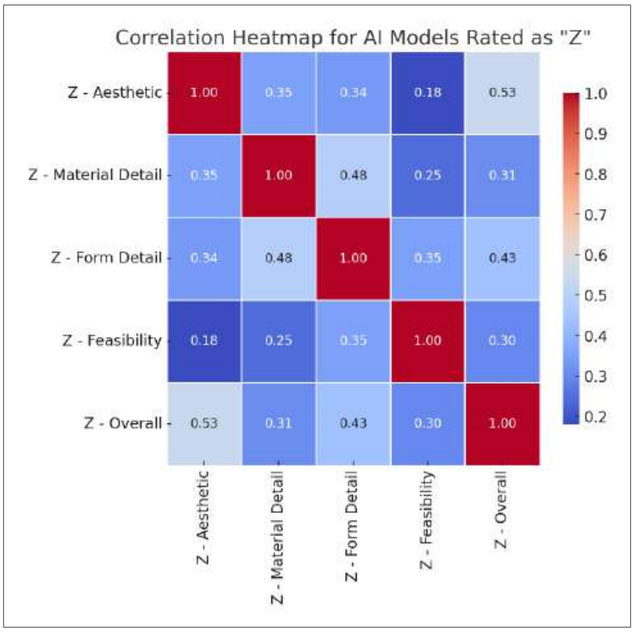

Figure 8. Correlation heatmap for LumaAI-Genie.

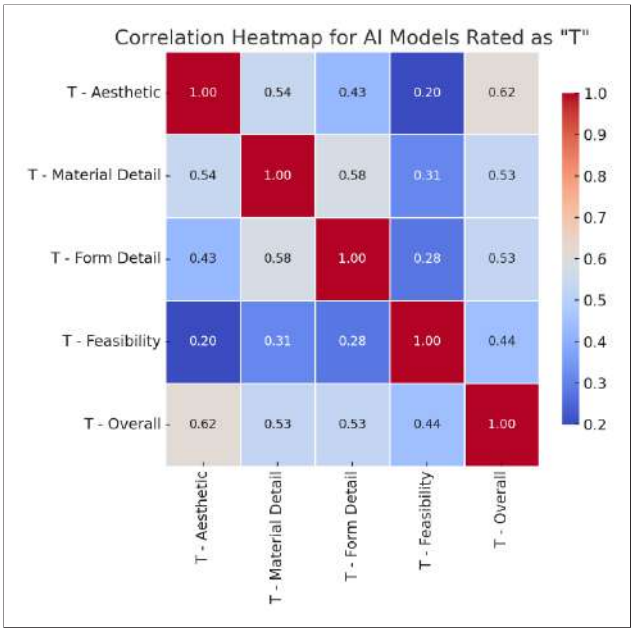

Figure 9. Correlation heatmap for Meshy AI.

+1.00 (shown in dark red on the heatmaps) show a strong positive relationship. This means that people who did well on one criterion also did well on the other. Values that are close to 0 (shown in light blue or white) indicate a weak or non-existent relationship, meaning that the scores for those two criteria were not significantly related to each other.

The correlation map analyzing the scores given to the Tripo AI model is attached. Upon examining the map, we observe a strong relationship between the Overall and Aesthetic categories for the Tripo AI tool. This indicates that the Aesthetic category has a significant impact on the Overall scores for the Tripo AI tool. Although the highest score was in the Feasibility category, the correlation coefficient measures the direct impact of a criterion on overall success, while average scores show how high that criterion is independently. The lowest correlation coefficient coming from the relationship between Feasibility and Material Detail suggests that participants who did not favor the detail level of the model still considered it feasible.This suggests that strategically improving aesthetics could be more effective in enhancing overall success (Figure 6).

In the DeepAI model, we observe the highest correlation coefficient of 0.76. This indicates a very strong relationship between form detail and material detail in the DeepAI model. Given the low scores received by the Y model, we can infer that participants found the form detail and material detail levels to be very poor. The fact that the correlation coefficients between Overall and other categories do not fall below 0.55 also indicates that the overall success of the model remains weak (Figure 7).

Aesthetic appeal has the greatest impact on the overall success score of the LumaAI model. In other words, as the LumaAI model is rated higher in aesthetics, its overall success score also increases. There is a significant relationship between material detail and form detail, suggesting that material details are consistent with form details and are evaluated together. There is a weak relationship between aesthetics and feasibility, indicating that participants may have evaluated aesthetics independently of feasibility. This suggests that focusing on aesthetics and form details could be crucial for improving the overall success of the Z model (Figure 8).

Among the four models, the Meshy AI received the highest scores from participants. Participants prioritized aesthetics, material detail, and form detail when evaluating overall success. The generally lower correlation of feasibility suggests that participants considered this criterion less important or secondary compared to others. This indicates that improving aesthetics and details could be a more effective strategy for enhancing overall success in models like the Meshy AI model (Figure 9).

Influence of Participant Profiles on Evaluation

To better understand how background factors shaped perceptions of AI-generated models, the survey data were analyzed by years of experience, and prior familiarity with AI-based 3D modeling. Participants were asked about their prior exposure to AI-based 3D modeling tools. Three categories emerged; unaware of such tools (n=43), aware but inexperienced (n=35), experienced users (n=28).

The analysis of user profiles revealed a significant difference in perception, with experienced users giving Meshy an overall score of 4.34, compared to 3.71 for inexperienced users. This disparity highlights the influence of computational literacy on design judgment, particularly the "novelty alignment bias" where experienced users may tolerate structural imperfections for creative potential. Experienced professionals were particularly harsh on DeepAI's feasibility (1.42), reinforcing the expectation that outputs must meet conventional technical standards. This suggests that familiarity with prompt-based generation may make users more tolerant of structural imperfections in favor of creative potential -an effect previously described as the "novelty alignment bias" in AI evaluation(Cho, et al., 2022).

Inexperienced participants, on the other hand, appeared more skeptical of ambiguous or abstract forms, often penalizing models with excessive visual complexity or unusual geometry, which may have affected their scores for Luma Genie and DeepAI.

The divergence reinforces that user expectations are shaped not only by design literacy but also by computational literacy, especially when interpreting outputs from generative algorithms. Lastly, professional seniority (students vs. early-career vs. experienced professionals) revealed subtle but meaningful trends. Students were more generous in rating aesthetic and overall success, especially for visually striking models generated by Tripo. Meanwhile, experienced professionals gave lower scores for tools that failed to meet conventional technical expectations, particularly DeepAI, whose average feasibility score dropped to 1.42 in this subgroup.

DISCUSSION

The findings of this study provide valuable insights into the capabilities and limitations of text-to-3D AI platforms in urban furniture design. The comparative analysis of Luma Genie, Meshy, Tripo, and Deepai revealed distinct strengths and weaknesses across different evaluation criteria, highlighting the diverse potential of these AI tools.

Aesthetic Appeal: The Meshy AI tool consistently outperformed the other platforms in terms of aesthetic appeal, indicating its strong capability in generating visually attractive designs. This suggests that Meshy's algorithms are particularly effective in interpreting and visualizing text descriptions to create appealing 3D models. The strong correlation between aesthetic appeal and overall success for the Tripo AI tool further emphasizes the importance of visual attractiveness in user evaluations as other studies suggest (Neef, et al., 2025; Rapp, et al., 2025; Stamkou, et al., 2025).

Texture and Form Detail: Textural detail is an another important factor to perceive the details of the AI generated designs (Pepe, et al., 2023). The analysis of texture and form detail showed that the "Meshy" tool also excelled in these areas, scoring the highest among the platforms. This indicates that Meshy is proficient in generating intricate and realistic textures and forms, which are crucial for creating high-quality urban furniture designs. The tool DeepAI, on the other hand, scored the lowest in these categories, highlighting significant areas for improvement in its texture and form generation capabilities.

Technical Consistency and Feasibility: In this key area, the Meshy tool emerged as the top performer, demonstrating its ability to create technically sound designs that can be applied in real-life scenarios. The DeepAI models have a low feasibility score of 1.93, which is likely due to their structural instability, unclear material type, and non-standard geometries, making it challenging to produce them cost-effectively in the real world. On the other hand, Meshy's high score (4.08) suggests that its outputs have better implicit structural logic and material consistency, which is linked to their perceived durability. This is a critical aspect for practical implementation, as it ensures that the designs can be realistically constructed and used in urban environments (Zhang, et al., 2025). The DeepAI tool's low score in this category indicates challenges in producing technically sound designs, which could hinder its practical application.

Overall Success: The Meshy AI tool excels due to its effective algorithms and intuitive user interface, but it also distinguishes itself by allowing users to adjust crucial settings such as Art Style, Target Polycount, Topology, and Symmetry. This appears to result in more complex and structurally sound 3D models. DeepAI's much lower scores, on the other hand, can be explained by the fact that it doesn't allow for customization and only makes one model based on the prompt.

Furthermore, a direct visual assessment of the outputs (Figure 1; Figure 2; Figure 3; Figure 4) confirms disparities in visual usability. For DeepAI, the benches often appear non-functional or too small for human use, directly impacting real-world ergonomic features. Luma Genie and Tripo generally provided better-defined shelter and seating elements, contributing to their higher scores in user comfort.

Actionable insights suggest that designers prioritise tools like Meshy, which allow for customised technical parameters, to achieve results with higher consistency and feasibility. The study also surfaces ethical considerations related to the "novelty alignment bias" and the risk of generative AI leading to the homogenization of design if functional and structural criteria are overlooked.

CONCLUSION

This study provides a comprehensive evaluation of four prominent text-to-3D AI platforms -Luma Genie, Meshy, Tripo, and Deepai -within the specialized context of urban furniture design. Our research shows that the Meshy AI tool consistently outperforms other platforms on several key criteria. This means that it is especially well-suited for creating high-quality, visually appealing urban furniture designs that are both technically feasible and aesthetically pleasing. The main reason for this success is that users can customize it. On the other hand, the DeepAI tool had major problems with structural integrity and functional logic, getting the lowest scores on most criteria. This indicates Meshy's particular suitability for generating high-quality, visually appealing, and technically feasible urban furniture designs, aligning with the growing demand for efficient and effective AI-driven design solutions in smart cities (Cina, et al., 2025; Shokry, 2025).

The analysis also highlights significant areas for improvement for the other platforms, particularly the DeepAI tool, which scored the lowest across most criteria. These findings provide valuable insights into the strengths and weaknesses of current text-to-3D AI technologies, offering guidance for future development and enhancement. The study highlights the revolutionary capacity of text-to-3D AI models in influencing the future of urban furniture design. It emphasises that platform development must concentrate on strategic enhancements in aesthetics, intricacy, and technical viability to fulfil the intricate demands of design professionals and establish functional urban spaces.

In conclusion, this research contributes to the growing body of knowledge on AI-driven design, providing a foundation for future studies and practical applications in urban furniture design. The insights gained from this study can inform the development of more effective and user-friendly AI tools, ultimately enhancing the quality and functionality of urban spaces.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Allam, Z., & Dhunny, Z. A. (2019). On big data, artificial intelligence and smart cities. *Cities*, *89*, 80–91. https://doi.org/10.1016/j.cities.2019.01.032

Althi, T. R., Kothamachu, V., & Pandita, R. (2023). Accelerating automotive design: Harnessing AI models for efficient 3D design and development of automobile systems and subsystems. *ITEC-India 2023 - 5th International Transportation Electrification Conference: EAMRIT - Accelerating e-Mobility Revolution for India's Transportation*. Chennai, India. https://doi.org/10.1109/ITEC-India59098.2023.10471378

Behravan, M. (2025). Generative AI framework for 3D object generation in augmented reality [Master's Thesis]. Virginia Polytechnic Institute and State University. https://doi.org/10.48550/arXiv.2502.15869

Behravan, M., Matković, K., & Gračanin, D. (2025). Generative AI for context-aware 3D object creation using vision-language models in augmented reality. *Proceedings - 2025 IEEE International Conference on Artificial Intelligence and Extended and Virtual Re-*

ality, AIxVR 2025, 73–81. https://doi.org/10.1109/AIxVR63409.2025.00018

Bier, H., Hidding, A., Brancart, S., Luna-Navarro, A., Khademi, S., & van Engelenburg, C. (2024). AI-supported approach for human-building interaction implemented at furniture scale. *Frontiers in Computer Science*, *6, 1295014*. https://doi.org/10.3389/fcomp.2024.1295014

Brisotto, C., Carney, J., Foroutan, F., Ochoa, K. S., & Schroder, W. (2023). Exploring the role of AI in urban design research: A comparative analysis of analogical and machine learning approaches. *Plan Journal*, *8*(2), 237–264. https://doi.org/10.15274/tpj.2023.08.02.5

Buljat, P. (2024). Capabilities of AI in text-to-3D model generators. *The Twelfth International Symposium GRID. Novi Sad, Serbia.*

Cai, Z. (2023, November 28). 3Description: An intuitive human-AI collaborative 3D modeling approach. *ACM International Conference Proceeding Series, 32, 1–5.* https://doi.org/10.1145/3632776.3632785

Cho, J., Zala, A., & Bansal, M. (2022). DALL-Eval: Probing the reasoning skills and social biases of text-to-image generative transformers. *arXiv, 2202*, 04053.

Cina, E., Elbasi, E., Elmazi, G., & AlArnaout, Z. (2025). The role of AI in predictive modelling for sustainable urban development: Challenges and opportunities. *Sustainability (Switzerland)*, *17*(11), 5148. https://doi.org/10.3390/su17115148

Cordero, A., Moreno, D., & Rubio, S. (2025). Urban furniture design through the implementation of artificial intelligence and additive manufacturing. *DYNA*, *100*, 130–136. https://doi.org/10.52152/D11301

DeepAI. (2025). *AI 3D Model Generator*. Retrieved April 10, from https://deepai.org/machine-learning-model/3d-objects-generator

Deng, H., Khan, S., & Erkoyuncu, J. A. (2024a). An investigation on utilizing large language model for industrial computer-aided design automation. *Procedia CIRP*, *128*, 221–226. https://doi.org/10.1016/j.procir.2024.07.049

Deng, H., Khan, S., & Erkoyuncu, J. A. (2024b). An investigation on utilizing large language model for industrial computer-aided design automation. *Procedia CIRP*, *128*, 221–226. https://doi.org/10.1016/j.procir.2024.07.049

Edwards, K. M., Man, B., & Ahmed, F. (2024). Sketch2Prototype: Rapid conceptual design exploration and prototyping with generative AI. *Proceedings of the Design Society*, *4*, 1989–1998. https://doi.org/10.1017/pds.2024.201

Fallacara, G., Fanti, M. P., Parisi, F., Parisi, N., & Sangiorgio, V. (2023, September). AI-driven image generation for enhancing design in digital fabrication: Urban furnishings in historic city centres. *The 2nd International Conference on Visual Pattern Extraction and Recognition for Cultural Heritage Understanding*. Pescara, Italy.

Fang, C., Dong, Y., Luo, K., Hu, X., Shrestha, R., & Tan, P. (2025). Ctrl-Room: Controllable text-to-3D room meshes generation with layout constraints. *arXiv, 2310*, 03602.

Foo, L. G., Rahmani, H., & Liu, J. (2023). AI-generated content (AIGC) for various data modalities: A survey. *1*(1), 1–35. https://doi.org/10.1145/3728633

Fu, T.J., Xiong, W., Nie, Y., Liu, J., Oğuz, B., & Wang, W. Y. (2023). Text-guided 3D human generation from 2D collections. *arXiv, 2305*, 14312.

Huang, D., Wang, N., Huang, X., Qu, J., & Zhang, S. (2024). Mesh-controllable multi-level-of-detail text-to-3D generation. *Computers & Graphics*, *123*(104039), 1–12. https://doi.org/10.1016/j.cag.2024.104039

Kamrowska-Załuska, D. (2021). Impact of AI-based tools and urban big data analytics on the design and planning of cities. *Land*, *10*(11), 1209. https://doi.org/10.3390/land10111209

Kazanidis, I., & Pellas, N. (2024). Harnessing generative artificial intelligence for digital literacy innovation: A comparative study between early childhood education and computer science undergraduates. *Ai*, *5*(3), 1427–1445. https://doi.org/10.3390/ai5030068

Kim, S., Li, K., Deng, X., Shi, Y., Cho, M., & Wang, P. (2024). Enhancing 3D fidelity of text-to-3D using cross-view correspondences. *IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*. Seattle, USA, 10649–10658. https://doi.org/10.1109/CVPR52733.2024.01013

Ko, J., Ajibefun, J., & Yan, W. (2023). Experiments on generative AI-powered parametric modeling and BIM for architectural design. *arXiv, 2308, 00227*. https://doi.org/10.48550/arXiv.2308.00227

Leão, C. P., Silva, V., & Costa, S. (2024). Exploring the intersection of ergonomics, design thinking, and AI/ML in design innovation. *Applied System Innovation*, 7(4), 65. https://doi.org/10.3390/asi7040065

Lee, S. H., Park, W. S., & Lee, K. S. (2024). Building knowledge base of 3D object assets using multimodal LLM AI model. *International Conference on ICT Convergence*, *2024*, 416–418. https://doi.org/10.1109/ICTC62082.2024.10827434

Li, C., Zhang, C., Cho, J., Waghwase, A., Lee, L. H., Rameau, F., Yang, Y., Bae, S. H., & Hong, C. S. (2023). Generative AI meets 3D: A survey on text-to-3D in AIGC era. *Journal of Latex Class Files*, *14*(8), 1–18. https://doi.org/10.48550/arXiv.2305.06131

Li, C., Zhang, C., Cho, J., Waghwase, A., Lee, L. H., Rameau, F., Yang, Y., Bae, S. H., & Hong, C. S. (2024a). Generative AI meets 3D: A survey on text-to-3D in AIGC era. *arXiv, 2305*, 06131

Li, Z., Sayuti, N. 'Ayn A., & Wang, J. (2024b). Exploring the application of artificial intelligence-generated content (AIGC) in modern furniture design innovation. *Pakistan Journal of Life and Social Sciences (PJLSS)*, *22*(1), 4191–4199. https://doi.org/10.57239/pjlss-2024-22.1.00307

Lindfors, J. (2025). Leveraging generative AI to create themed assets for games: A study on narrative and 3D asset creation with AI [Master's Thesis]. UMEA University.

Liu, Z., Wang, Y., Qi, X., & Fu, C. W. (2022). Towards implicit text-guided 3D shape generation. *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*. New Orleans, USA, 17896–17906. https://doi.org/10.1109/CVPR52688.2022.01737

Lu, F., Lin, K. Y., Xu, Y., Li, H., Chen, G., & Jiang, C. (2024). Urban architect: Steerable 3D urban scene generation with layout prior. *arXiv, 2404*, 06780.

Luma Labs. (2025). *Genie Text-to-3D Model*. Retrieved April, 10, 2026 https://lumalabs.ai/genie

Luusua, A., & Ylipulli, J. (2020). Urban AI: Formulating an agenda for the interdisciplinary research of artificial intelligence in cities. *DIS' 20 Companion: Companion Publication of the 2020 ACM Designing Interactive Systems Conference*. Portugal, Funchal, 373–376. https://doi.org/10.1145/1234567.8901234

Ma, Y., Fan, Y., Ji, J., Wang, H., Yin, H., Sun, X., & Ji, R. (2024). Creating high-quality 3D content by bridging the gap between text-to-2D and text-to-3D generation. *ACM Transactions on Multimedia Computing, Communications, and Applications, 315, 1–23.* https://doi.org/10.1145/3687475

Meshy. (2025). *Meshy AI 3D Model Generator*. https://www.meshy.ai/features/text-to-3d

Neef, N. E., Zabel, S., Papoli, M., & Otto, S. (2025). Drawing the full picture on diverging findings: Adjusting the view on the perception of art created by artificial intelligence. *AI and Society*, *40*(4), 2859–2879. https://doi.org/10.1007/s00146-024-02020-z

Öcal, B. M., Tatarchenko, M., Karaoglu, S., & Gevers, T. (2024). SceneTeller: Language-to-3D scene generation. *ECCV 18th European Conference*, *15143*, 362–378. https://doi.org/10.1007/978-3-031-73013-9_21

Pepe, M., Alfio, V. S., & Costantino, D. (2023). Assessment of 3D model for photogrammetric purposes using AI tools based on NeRF algorithm. *Heritage*, *6*(8), 5719–5731. https://doi.org/10.3390/heritage6080301

Rapp, A., Di Lodovico, C., Torrielli, F., & Di Caro, L. (2025). How do people experience the images created by generative artificial intelligence? An exploration of people's perceptions, appraisals, and emotions related to a Gen-AI text-to-image model and its creations. *International Journal of Human Computer Studies*, *193, 103375*. https://doi.org/10.1016/j.ijhcs.2024.103375

Reed, S., Akata, Z., Yan, X., Logeswaran, L., Schiele, B., & Lee, H. (2016). Generative adversarial text to image synthesis. *Proceedings of The 33rd International Conference on Machine Learning. arXiv, 1605, 05396.* https://doi.org/10.48550/arXiv.1605.05396

Sahebnasi, M. J., Farrokhimaleki, M., Wang, N., Zhao, R., & Maurer, F. (2024). Exploring the potential of generative AI in prototyping XR applications. *RealXR: Prototyping and Developing Real-World Applications for Extended Reality, 3704, 4.* https://doi.org/https://ceur-ws.org/Vol-3704/paper4.pdf

Sanchez, T. W., Fu, X., Yigitcanlar, T., & Ye, X. (2024). The research landscape of AI in urban planning: A topic analysis of the literature with ChatGPT. *Urban Science*, *8*(4), 197. https://doi.org/10.3390/urbansci8040197

Šarčević, I., Dorić, T., Ivančević, A., Banić, D., & Buljat, P. (2024). Capabilities of AI in text-to-3D model generators for mechanical components design. *International Symposium on Graphic Engineering and Design*, *2024*, 44. https://doi.org/10.24867/GRID-2024-p44

Shen, Y., Shen, Y., Cheng, J., Jiang, C., Fan, M., & Wang, Z. (2024). Neural Canvas: Supporting scenic design prototyping by integrating 3D sketching and generative AI. *Conference on Human Factors in Computing Systems – Proceedings, 1056, 1-18.* https://doi.org/10.1145/3613904.3642096

Shokry, R. B. (2025). Exploring the impact of artificial intelligence on urban design. *Journal of Engineering Sciences*, *53*(4), 457–473. https://doi.org/10.21608/jesaun.2025.370145.1459

Stamkou, C., Saprikis, V., Fragulis, G. F., & Antoniadis, I. (2025). User experience and perceptions of AI-generated e-commerce content: A survey-based evaluation of functionality, aesthetics, and security. *Data*, *10*(6), 89. https://doi.org/10.3390/data10060089

Tripo3d. (2025). *Tripo3d AI model generator*. Retrieved April 10, from https://www.tripo3d.ai/blog/text-to-3d-model

Vimpari, V., Kultima, A., Hämäläinen, P., & Guckelsberger, C. (2023). An adapt-or-die type of situation: Perception, adoption, and use of text-to-image-generation AI by game industry professionals. *Proceedings of the ACM on Human-Computer Interaction*, *7*, 131–164. https://doi.org/10.1145/3611025

Yavartanoo, M., Hong, S., Neshatavar, R., & Lee, K. M. (2024). Text2CAD: Text to 3D CAD generation via technical drawings. *arXiv, 2411, 06206.* https://doi.org/10.48550/arXiv.2411.06206

Yeo, J. Q., Wang, Y., Tanary, S., Cheng, J., Lau, M., Ng, A. B., & Guan, F. (2023). AICRID: AI-empowered CR for interior design. *Proceedings - 2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct, ISMAR-Adjunct, 2023*, 837–841. https://doi.org/10.1109/ISMAR-Adjunct60411.2023.00184

Yıldırım, E. (2023). Comparative analysis of Leonardo AI, Midjourney, and Dall-E: AI's perspective on future cities. *Urbanizm*, *28*, 82–96. https://doi.org/10.58225/urbanizm.2023-28-82-96

Yuchen, G., Lifan, L., Wenrui, T., & Wenhan, Q. (2019). Urban environmental management with AI-assisted design. *IOP Conference Series: Earth and Environmental Science*, *233*(2), 022021. https://doi.org/10.1088/1755-1315/233/2/022021

Zeyin, S., Jinghan, Q., Hao, Z., & Shu, X. (2024). Human-centered generative AI framework in intelligent construction: A case study on furniture manufacturing design. *ASim2024, The 5th Asia Conference of the IBPSA*. Osaka, Japan, 1505–1512.

Zhang, H. (2020). Text-to-form: 3D prediction by linguistic descriptions. *Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture*, *2020*, 238–247. https://doi.org/https://papers.cumincad.org/data/works/att/acadia20_238.pdf

Zhang, Z., Zhou, X., Fang, Y., Xiong, Z., & Zhang, T. (2025). AI-driven 3D bioprinting for regenerative medicine: From bench to bedside. *Bioactive Materials*, *45*, 201–230). https://doi.org/10.1016/j.bioactmat.2024.11.021

Zhuang, X., Ju, Y., Yang, A., & Luisa Caldas. (2023). Synthesis and generation for 3D architecture volume with generative modeling. *International Journal of Architectural Computing*, *2023*, 1–18. https://doi.org/10.1177/14780771231168233

Megaron, Vol. 21, No. 1, pp. 101–121, March 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.47527

Article

Digitalization and interdisciplinary design process in 21st century architecture offices: Transforming practices and future perspectives

Başak Kapıcıoğlu, Elif Tatar

Department of Architecture, Eskişehir Technical University, Eskişehir, Türkiye

ARTICLE INFO

Article history
Received: 16 June 2025
Revised: 6 March 2026
Accepted: 2 April 2026

Key words:
Architecture Offices; digitalization; interdisciplinarity; interdisciplinary design processes.

ABSTRACT

This study analyzes the impact of digitalization and interdisciplinary design approaches on production processes in architectural offices in the 21st century, exploring the implications of this transformation on institutional structure, actor representation and collaboration models, particularly in relation to theory and practice. Architectural offices are considered dynamic spaces where digital technologies, beyond being mere technical tools are also positioned as structural components that transform production culture, while interdisciplinarity is inherently organized within operational practices. The research is based on the content analysis of 45 articles published between 2005 and 2025 and on the comparative evaluation of BIG, MVRDV and Herzog & de Meuron from Europe and Tabanlıoğlu, GAD, and Erginoğlu & Çalışlar from Türkiye. In the content analysis, themes were systematically coded through frequency and co-occurrence relationships, resulting in a conceptual structure concentrated around participatory design, interdisciplinary teamwork and the ecology framework. This structure made visible how production tools such as BIM integration, digital twins, AI-based workflows and parametric modeling are positioned across both computational and organizational dimensions. The findings reveal that in European offices, digital tools are integrated into institutionalized computational cycles from the early stages of design, whereas in the Türkiye examples, these tools diversify more flexibly in relation to local context, multi- actor negotiation and project-based strategies. The study demonstrates that the digitalizing production culture reshapes design processes from linear sequences into data-driven, multilayered and iterative structures. This framework suggests that, for the future of architectural practice, data-driven participation models and the integration of computational–interdisciplinary processes into the early stages of design are becoming increasingly central design approaches.

Cite this article as: Kapıcıoğlu, B., & Tatar, E. (2026). Digitalization and interdisciplinary design process in 21st century architecture offices: Transforming practices and future perspectives. Megaron, 21(1):101–121.

***Corresponding author**
*E-mail adress: basakkapcoglu@gmail.com

Published by Yıldız Technical University, İstanbul, Türkiye

INTRODUCTION

The phenomenon of interdisciplinarity has increasingly taken center stage in the scientific and professional production models of the 21st century. This phenomenon is addressed at both theoretical and practical levels in a wide variety of fields, such as architecture, engineering, education, health sciences, environmental design, and technology, and paves the way for innovative production forms that emerge from the coming together of different specialties (Tebes & Thai, 2018; Badawi & Abdullah, 2021). Interdisciplinarity has the capacity not only to bring together different fields of knowledge, but also to simultaneously transform their methodological approaches, conceptual languages, and problem-solving strategies. This interaction, shaped by the internal dynamics of each discipline, enables the production of more holistic solutions for common goals (Pinter-Wollman et al., 2018).

Interdisciplinarity in architecture plays a critical role in areas where global crises, complex urban issues, the sustainable transformation of the built environment, and the integration of digital production technologies are discussed. Architecture offices are required to work in interaction with topics such as social behavior, materials science, energy efficiency, biotechnology, and social participation, not just physical space design; this transforms the design process into a multidimensional and multi-actor structure (McAlister et al. 2025). Applications in the field of education, in particular, ensure early exposure to interdisciplinarity through collaborative studio and workshop models involving students and educators from different disciplines (Jutraz, Zupančič & Juvančič, 2014). However, how interdisciplinarity works in practice, the level of interaction established, and the effects of this interaction on organizational structures have not yet been sufficiently evaluated in a systematic manner. The literature frequently emphasizes the importance of interdisciplinarity; however, dynamics such as limitations encountered in practice, coordination problems between actors, methodological incompatibilities, and communication gaps are often overlooked (Tebes & Thai, 2018; Pinter-Wollman et al., 2018). At this point, fundamental research questions emerge regarding how interdisciplinary design processes are structured, what role architecture offices play in these processes, and how digitalization has become a transformative element in these processes.

Architectural practice is undergoing a fundamental structural transformation in the 21st century with the integration of digital technologies into production processes and the proliferation of multi-actor design organizations. Architectural offices, in particular, are transforming into complex systems that redefine not only technical production strategies but also decision-making mechanisms, actor representation, and information flow structures under the influence of computational tools, parametric modeling processes, and network-based production forms. This transformation brings to the fore new production paradigms in which design is intertwined with interdisciplinary modes of operation at the organizational level.

This study aims to analytically examine the structural, methodological, and organizational transformation of digitalization processes shaped by 21st-century production paradigms in architecture offices, as well as interdisciplinary design processes. The emphasis on the 21st century here represents not merely a historical periodization but a critical transformation context signifying the restructuring of the architectural production environment around information technologies, computational design tools, and multi-actor-based operations. In the literature, the concept of interdisciplinarity is mostly addressed at the level of theoretical definitions and models. However, the extent to which this concept is inherent in current production practices in architecture offices, the forms on which it is based, and how it integrates with digitalization have not been sufficiently analyzed in a systematic manner. Existing studies focus either on individual professional experiences or on singular project processes; thematic analyses based on content analysis of institutional operations, organizational charts, and representational relationships between actors at the office scale remain limited. In this context, the originality of the study lies, on the one hand, in systematizing conceptual patterns through content analysis along the axes of digitalization and interdisciplinarity and, on the other hand, in establishing a criterion-based evaluation model that allows these patterns to be matched with organizational structures and production processes that can be concretely observed in architecture offices. Ultimately, the research aims to reveal how interdisciplinary practices are shaped in digital production environments, which actor structures and decision-making mechanisms they represent, and how they intersect with current trends on a theoretical level. The study structure created in line with the research objective is presented in Figure 1.

In order to establish a multidimensional relationship between the theoretical depth of the research and its practical application, the study has been designed as a comprehensive structure consisting of five sections. The first section examines the effects of digitalization and interdisciplinary design on 21st-century architectural practice, defining the corresponding changes at the office level; the research problem, objectives, and problematic context are established at a technical level. The second chapter evaluates the historical development of the concept of interdisciplinary design, its epistemological dimensions, and its theoretical frameworks in architectural literature. The third chapter explains the methodological structure of the research; the content analysis-based thematic structuring process and how this process is transformed into a criterion system for case-based analysis

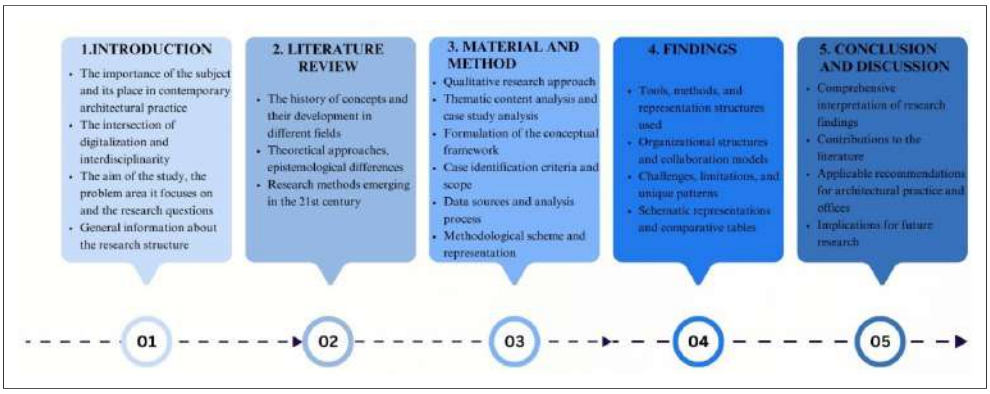

Figure 1. Study structure created within the scope of the research (Designed by the Authors).

are addressed at a technical level. The fourth chapter consists of findings that comparatively analyze the conceptual themes obtained through organizational structures, actor representation, tool usage patterns, and knowledge sharing models in architecture offices. Finally, the fifth chapter provides a holistic interpretation of the findings, presents original contributions to the literature and architectural practice, and suggests possible directions for future research.

LITERATURE REVIEW

Interdisciplinarity provides a theoretical and methodological foundation that is becoming increasingly important in the 21st century's forms of knowledge production and in the architectural environment, alongside structural, technological, and epistemological transformations. The phenomenon of interdisciplinarity has been shaped by epistemological approaches and conditions of knowledge production that have changed over different periods. Kuhn (1962) questioned the epistemological foundations of knowledge production, laying the groundwork for metadisciplinary thinking and explaining the transformation of scientific paradigms. Historically, the concept of multidisciplinarity came to the fore in the mid-20th century, when fields of knowledge were sharply defined, and it referred to different disciplines coming together to solve a specific problem (Piaget, 1973; Vygotsky, 1978; Klein, 1990). These early approaches offered a framework that limited interdisciplinary collaboration rather than a deep integration of knowledge fields. In the 1990s, interdisciplinarity evolved into a more comprehensive understanding that focused on the integration and synthesis of knowledge rather than just the exchange of information. During this period, the interdisciplinary approach was shaped by principles such as integration, contextualization, scale sensitivity, and the re-evaluation of discipline-specific perspectives (Brewer, 1995; Klein, 1996).

The 21st century, in which architectural production processes have been restructured alongside digitalization, represents an era in which interdisciplinarity has evolved beyond being merely a form of collaboration to become the fundamental organizational logic of architectural production practice. With the transition to the information society, interdisciplinarity has evolved into a production paradigm directly shaped by social, environmental, and technological transformations. During this period, Nowotny, Scott, and Gibbons (2001) argued that knowledge was no longer confined to the laboratory but produced within societal contexts, marking the beginning of a new phase in which interdisciplinarity became associated with dynamic, interactive, and transformative knowledge systems. Chettiparamb (2007) interpreted interdisciplinarity not merely as a theoretical orientation but as a phenomenological condition emerging from the inherent interactions between disciplines. The dissolution of disciplinary boundaries enabled not only collaborative working models but also the formation of new domains of meaning and conceptual intersections (Chandler, 2004; Repko, 2008). Within this trajectory, transdisciplinarity emerged as an inclusive model that moves beyond disciplinary categories by integrating local knowledge, cultural experiences, and social practices into the process, foregrounding participatory modes of problem-solving (Nicolescu, 1999; Helmane & Briška, 2017).

The expansion of digital technologies beyond formal production toward redefining the relationships between design, material, and fabrication has transformed the intellectual and technical boundaries of architectural offices. This shift—amplified by the rise of performance-oriented, open-ended, and interactive design approaches—has led to the dissolution of linear design processes and the emergence of integrated workflows in which multiple domains of expertise operate simultaneously (Phocas, 2015). In this period, digitalization has evolved not merely into a tool for formal variation but into the infrastructural backbone of a knowledge-based production system, giving rise to hybrid workflows that integrate engineering analysis, simulation environments, and fabrication processes within design practice. Consequently, the traditional dichotomy between creativity and technical precision has been reconfigured into a production logic continuously informed by performance parameters. This transformation has become a defining condition for contemporary architectural practice. Digitalization has not merely enabled the coexistence of multiple disciplines; it has facilitated their integration through interactive, data- driven, and continuously evolving information systems. Today, interdisciplinarity in architectural offices is positioned as a production model that synthesizes diverse domains of expertise. In particular, GIS-based analyses, unmanned aerial systems, AI-assisted simulation tools, and scenario-generation techniques deepen the analytical dimension of design processes and are increasingly embedded within the decision-making structures of design offices (Kauffman, 2016; Buchanan, 2019). As a result, the scope of interdisciplinarity has expanded, and its sphere of influence has intensified, strengthened on an epistemological level by principles such as flexibility, continuous learning, and knowledge sharing.

By the 2020s, when digitalization had reached a mature stage, architectural offices had begun to transform into research-driven environments where data analytics, engineering parameters, and digital fabrication were coordinated as integrated processes. Parametric and algorithmic design approaches enabled the dynamic adaptation of systems defined by performance criteria, while digital production dissolved the historical separation between design and construction. During this period, offices evolved into "knowledge hubs" situated at the center of information production, and multi-actor, data-driven design models became widespread through BIM, parametric modelling, and digital fabrication technologies (Knippers et al., 2021). However, the superficial adoption of this transformation has, in some practices, placed the creative process at risk of becoming overly technical. Although digital tools have the potential to deepen collaboration, when they remain confined solely to formal production, they may compress the discipline into a reductionist framework. This situation continues to generate a persistent zone of tension within the organizational structures of architectural offices (Knippers et al., 2021). These technologies enable architectural offices to engage not only with physical design, but also with themes such as energy efficiency, temporary housing, and environmental sustainability. This new interdisciplinary model— integrated with digital production processes—transforms digitalization in architecture from a mere tool into a strategic and holistic component of the design process itself (Borgman, 2015).

In the same period, the concept of the digital twin began to be understood as an integral component of systemic thinking within architectural offices. The integration of digital twins into the management of smart infrastructures placed them not only at the center of performance analyses but also of knowledge sharing among stakeholders (Broo, Bravo-Haro & Schooling, 2022). Digital twin technologies have further transformed the organizational structure of architectural design and production processes. When integrated with cyber-physical systems, digital twin models link CAD environments, software frameworks, simulation tools, and functional models from different disciplines within a unified digital environment, ensuring continuous information exchange (Ashtari Talkhestani et al., 2019). This approach enables the entire project—from initial design to operational phases—to be conceived collaboratively and allows interdisciplinary teams to produce data-driven decisions synchronously. In this respect, the growing role of digital twins signals an organizational-scale transformation within architectural practice. Similarly, artificial intelligence and big-data infrastructures based on bidirectional data flows between physical and digital systems have brought advanced applications such as predictive modelling, performance analytics, and dynamic decision systems into architectural offices (Qian et al., 2022). These technologies shift the design process from static representation to a continuously learning and adaptive system. Thus, digitalization is no longer merely a tool that accelerates production; it now constitutes a cognitive infrastructure that reshapes decision-making processes.

Debates on the organizational dimension of interdisciplinarity have simultaneously revealed the limits of the digital collaboration culture within design offices. Although diverse expertise is brought together in sustainable and nature-based design practices, decision-making and knowledge production often remain centralized. This condition reflects the prevalence of formal, surface-level collaboration models in the literature, termed "tokenistic collaboration" (Butt & Dimitrijević, 2022). A genuine transition toward interdisciplinarity requires not only the adoption of digital tools but also the transformation of the social and organizational relationships surrounding them. In this sense, digitalization is more than a technical process; it is a mechanism that reshapes the epistemological structure of architectural offices.

Interdisciplinary integration has also introduced new challenges in architectural programming, such as data management, information security, and social representation. While the interaction between physical and digital environments enhances information exchange, gaps in standardization and security constraints continue to limit digital transformation. The insufficient representation of social participation on digital platforms leads to the exclusion of user experience and societal engagement from design and production processes (Jin, 2024). This reveals that digital transformation is not solely a technological evolution but also a process requiring a redefinition of social inclusivity. Within this transformation, digitalization has played a decisive role; AI-supported generative design tools, BIM integration, sensor technologies, the Internet of Things, and big data analytics have enabled multi-actor, data-driven, and interactive design practices within architectural offices (Li et al., 2024). In this context, urban data ecosystems established within the socio-technical and urban governance framework shaped by smart cities, along with real-time data flows, are increasingly making interdisciplinary collaboration models visible at the scale of architecture firms. These models can interpret design decisions alongside environmental performance, usage scenarios, and operational data.

This chronological trajectory demonstrates that, for architecture offices, digitalization has become more than a purely technological innovation; it has turned into a structural necessity that compels the transformation of modes of production, the circulation of knowledge, and decision-making mechanisms. The simultaneous management of complex urban systems, sustainable modes of production, and data-driven decision-making processes is no longer achievable through individual expertise alone, but rather through integrated network structures. At the same time, the literature indicates that digital transformation has not been institutionalized in a holistic and in-depth manner across all contexts, and that BIM-based digitalization can advance in a fragmented way, particularly due to process standardization issues and mismatches between macro- and micro-level planes (Awe et al., 2025; Kassem & Ahmed, 2022). Moreover, in multi-stakeholder production environments, knowledge sharing and interdisciplinary coordination can become fragile depending on the management of common data environments, the transfer of knowledge and experience, and the establishment of institutional collaboration mechanisms, while coordination difficulties may constrain the continuity of BIM-supported collaborative processes (Miao et al., 2024; Shim et al., 2024).

In sustainability- and nature-based design agendas as well, interdisciplinarity is emphasized in some cases as remaining at a merely formal level; due to asymmetries in decision-sharing and levels of representation, the risk of tokenistic collaboration persists (Butt & Dimitrijević, 2022). For digitalization to become a lasting paradigm in architecture offices, these shortcomings must be overcome and technological infrastructures must be integrated with ethical, social, and organizational principles. To the extent that architectural practice achieves this integration, it will transform digitalization from a mere instrument of production into a carrier of interdisciplinary creativity.

MATERIAL AND METHOD

Research Design and Methodological Approach

In the study, a two-stage qualitative research design was constructed. The methodological framework of the first stage is based on the systematic structuring of the content analysis process. In this context, a bibliometric literature review was conducted around the themes of the role of interdisciplinarity in the architectural domain, digital production technologies, and the organizational structure of architectural offices. To identify the gap in the literature, international peer-reviewed articles published between 2005 and 2025 were compiled using the keywords *"architectural practice," "digitalization," "interdisciplinary design," "collaborative design models,"* and *"digital fabrication in architecture."* After the dataset was established, an inductive thematic analysis approach was adopted; the studies were decomposed into multilayered conceptual networks, and common themes were systematically coded. In the second stage, based on the themes derived from the analysis, the main criteria reflecting the relationship between interdisciplinarity and digitalization in production processes, as well as their corresponding sub-parameters, were identified. The research strategy integrates systematic literature review, thematic coding, and frequency analysis into a comprehensive structure, enabling the conceptual synthesis of the findings and the exploration of contemporary trends. The methodological workflow of the study is visually summarized in Figure 2.

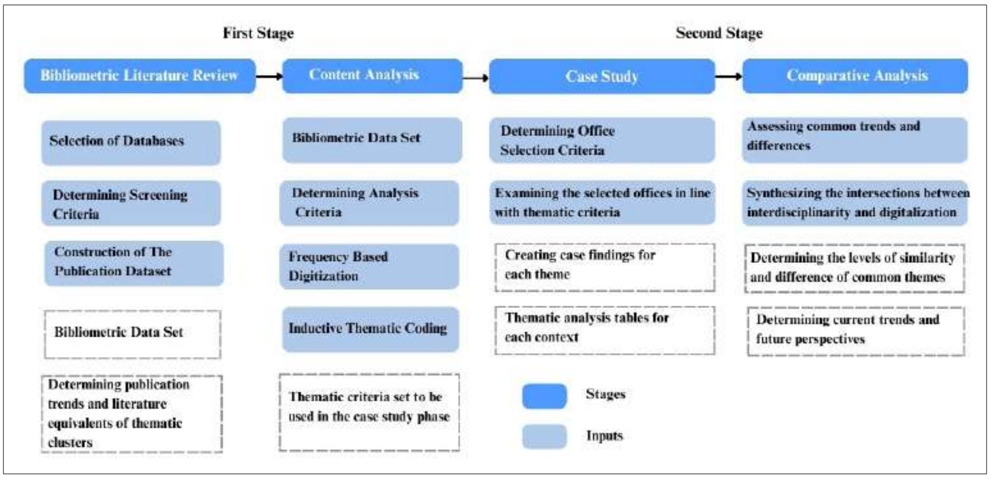

Figure 2. Methodological workflow structured in line with the aim of the study (Designed by the Authors).

The second stage consists of the comparative analysis of selected architectural offices from Europe and Türkiye. Within the framework of the thematic findings obtained from the content analysis, architectural offices characterized by digital production and interdisciplinary organizational structures were evaluated as part of the case study. The selected offices are those that have both national and international work and have adopted interdisciplinary and digitally based production models. After identifying the sample offices, the criteria derived from the content analysis were examined within the context of each office; the selected cases were first compared internally and subsequently synthesized to form a comparative evaluation between Europe and Türkiye. The findings emerging from the analysis provide a unique context for assessing how the organizational structures and production processes of architectural offices demonstrate a tendency toward restructuring in order to identify contemporary trends and adapt to them.

Creating a Data Set Based on Architecture, Interdisciplinarity and Digitalization

The research is conducted through a two-stage process. In the first stage, a systematic search was conducted in the Scopus, Web of Science, and ScienceDirect databases using the keywords *"architectural practice," "digitalization," "interdisciplinary design," "architecture and technology," "collaborative design models,"* and *"digital fabrication in architecture."* The search process was limited to the years 2005–2025. A total of 186 articles were screened in the preliminary review, and only those studies that demonstrated a direct or indirect conceptual relationship with production processes and addressed digitalization and interdisciplinary design approaches in a comprehensive manner were selected. In the second stage, a case study and comparative analysis were structured based on the results obtained from the content analysis. The architectural offices included in the study within the European and Türkiye contexts were examined through the thematic criteria, and their technical and organizational approaches to interdisciplinarity and digitalization were incorporated into the analysis, enabling a cross-contextual comparison.

As a result of the evaluations conducted in the first stage, 45 articles were selected as the sample to be included in the content analysis. In the selection process, the primary criterion was that the studies discuss the themes of digitalization and interdisciplinarity not only at a technical level but also through the conceptual representations of production processes, methodological approaches, and organizational models. In addition, the fact that the articles were published in reputable indexed journals (SCI, SSCI, AHCI, ESCI) and appeared in peer-reviewed outlets with high scientific credibility constituted a second determining factor that enhanced the quality of the dataset. Furthermore, the extent to which the reviewed studies could be directly associated with the contemporary design practices of architectural offices—particularly the use of digital production technologies, the implementation of interdisciplinary collaboration models, and the management of design–construction integration—was another essential criterion considered during the selection. The 45 studies situated at the intersection of these three criteria formed the most appropriate sample set representing the interaction between digitalization and interdisciplinarity within architectural production processes.

During the construction of the dataset, the search was conducted at a macro scale through the lens of interdisciplinarity and the themes directly or indirectly associated with this concept, thereby aiming to approach architectural production processes from a holistic perspective. The selection of the last 20 years was a deliberate choice to capture rapidly evolving contemporary trends in digitalization and interdisciplinarity and to identify the dynamics of conceptual transformation in the field. This approach enabled the research to relate its theoretical depth to current professional practices.

The general characteristics of the dataset—including the databases consulted, the publication range, and the common themes highlighted in the content analysis—are summarized in Table 1. Throughout the thematic analysis process, interdisciplinarity and digital production technologies emerged as a shared focal point in the majority of studies, while variations were observed in the emphasis placed on themes such as the transformation of organizational structures, collaborative design models, and participatory production cultures.

During the content analysis dataset creation process, common themes and thematic differences identified across articles are presented in Table 2. Thematic similarities and differences identified during this process were structured through contextual analyses of how each article addressed the concepts of interdisciplinarity and digitalization at the level of production processes. Common themes were defined as clusters that recurred at a high frequency across studies and represented conceptual intersections, while divergent themes were systematically classified by considering their contextual variations based on context, scale, technology use, and organizational models.

The data obtained from the content analysis were subjected to a multilayered thematic coding process to understand how themes of interdisciplinarity and digitalization are patterned in architectural production processes. The next section presents in detail the common conceptual clusters derived from the dataset and their analysis methods.

Thematic Coding: Identification of Prominent Common Themes

During the content analysis process, the resulting dataset was analyzed using a multilayered coding method, taking

Table 1. General characteristics of the constructed dataset

Criterias	Features
Scanned Databases (INDEXES)	Publications indexed in Scopus, Web of Science, ScienceDirect databases, AHCI, SCI, SSCI, ESCI
Keywords Used	"Architectural practice", "digitalization", "interdisciplinary design", "architecture and technology", "collaborative design models", "digital fabrication in architecture"
Publication Year Range	2005–2025 (to monitor current conceptual and technological trends)
Total Number of Publications Scanned	186 publications were subjected to systematic preliminary review.
Number of Publications Analyzed in Depth	45 articles that met the selection criteria were included in the content analysis.
Selection Criteria	The studies should address the themes of digitalization and interdisciplinarity in a reciprocal manner, with theoretical and methodological integrity; the studies should be included in Scopus, Web of Science, and ScienceDirect databases; the content should be directly relatable to the use of digital tools in the current production practices of architectural offices, interdisciplinary interaction, design-practice integration, and organizational collaboration models.
Content Analysis Method	Inductive thematic analysis, multilayer coding, frequency-based digitization
Thematic Similarities	The concepts of interdisciplinarity, digital production technologies, knowledge sharing and cooperation between actors have formed a common ground in most studies.
Thematic Differences	Organizational structure transformations, participatory production culture, digital tool use, and scale-based practical differences varied across contexts.

intoaccount thematic focuses and conceptual intersections. Within this scope, the reviewed articles were first classified according to their core conceptual areas, focusing on how digitalization and interdisciplinarity are represented in architectural offices. In the first stage, studies that addressed the theme of interdisciplinarity solely at a theoretical level were categorized. In the second stage, publications that intersected the concepts of architecture and interdisciplinarity but did not emphasize digital production technologies were identified. In the third stage, studies that explored the relationship between interdisciplinarity and digital technologies and referenced design practices in architectural offices were coded. In the fourth stage, publications that simultaneously addressed the themes of architecture, dig-

Table 2. Thematic similarities and differences regarding the data set

Common Themes	Diverging Themes
Integration of interdisciplinarity dynamics into production processes	Differences in organizational structures' adaptation levels to digitalization
ntegration of digital production technologies (BIM, digital twin, parametric design) into processes	Differences in the intensity of use of digital technologies and in-process integration
The impact of information sharing and collaboration between actors on production culture	Positioning collaborative models as central or supportive
Participatory production culture and multi-actor design processes	The reflection of user participation and actor representation directly or indirectly on production processes
Prevalence of parametric design and computational manufacturing techniques	Computational techniques vary depending on project scale and context
Use of digital twins and data-based production models	Differentiation of digital twin applications into infrastructure-scale and building-scale focuses
Supporting innovation culture with digitalization	Adoption of innovation processes at different levels in organizational structures
Digitalization integration between education and practice	Whether or not practical production processes are directly contributed to in education-based studies
Relating sustainability themes to digitalization and interdisciplinarity	In some studies, the sustainability approach is addressed only at the conceptual level, while in some studies it is integrated into operational processes

italization, and interdisciplinarity, presenting a holistic approach to production practices, were identified.

In addition, articles that focused solely on interdisciplinarity but did not directly engage with digital transformation, or only superficially referenced interdisciplinarity within the context of digitalization, were also classified according to their thematic density. This multilayered classification process enabled the analytical evaluation of thematic patterns in terms of their impact on production processes in architectural offices. Each article was positioned based on its conceptual intersection and coded based on this position. The resulting thematic clusters formed the basis for frequency analyses and conceptual modeling conducted in the next stage, enabling the systematic generation of inferences regarding the interdisciplinary digitalization strategies of architectural offices. Based on this, a systematic structure was constructed to identify which conceptual areas were more intensively addressed and which thematic areas were less frequently represented in the dataset (Table 3).

Based on the detailed content analysis of the 45 articles included in the study, the sub-themes situated along the axis of digitalization and interdisciplinarity were systematically coded, and a co-occurrence matrix was constructed to make the interrelationships between themes visible. During the coding process, the patterns of simultaneous appearance among these themes were quantified through the matrix. The results indicate that digital production technologies—such as digital integration, BIM integration, digital twin applications, and parametric design— strongly intersect with system architecture and studio integration, while organizational and actor-oriented elements such as interdisciplinary teamwork, team science, and user-centered approaches also produce notable overlaps. These findings reveal that certain themes form a defining core within production processes, whereas others constitute a coherent background that supports this core. The numerical coding matrix showing the co-occurrence patterns of the sub-themes clustered under the main themes is presented in Table 4.

To enable a more objective and comparable analysis of the conceptual clusters derived from the thematic coding process, a frequency-based quantification method was employed in this study. The identified sub-themes were expressed through numerical values according to their intensity of representation within each article, allowing the distribution and co-occurrence frequencies of these themes across the dataset to be captured in a measurable structure. This approach provided an objective basis for comparing the common themes related to digitalization and interdisciplinarity in architectural offices and established a foundation for the subsequent stages of analysis.

Frequency-Based Digitization Method

The frequency-based analysis process was structured in two stages. In the first stage, each main theme and subtheme were converted to numerical values based on the number of times they were directly or indirectly represented in the reviewed articles. In this context, the density of representation of specific conceptual codes in the literature was measured and a thematic distribution map was created. The graph, created based on the findings of this stage, visualizes the unique frequency of each thematic code, revealing the most dominant conceptual clusters within the study. Figure 3 has

Table 3. Grouping of main themes and sub-themes according to general trends

Main Themes	Sub-Themes	Explanation
Interdisciplinarity Digitalization	Digital_Twin, System_Architecture, Metaverse_Environment	Digital production technologies and data-based structures were approached from a theoretical perspective; the framework of interdisciplinarity was discussed through digital twins and system models.
Architecture-Interdisciplinarity	Cross_Discipline_Practice, Studio_Integration, Education_Model, Sustainability_In_Education	Focus was placed on interdisciplinary collaborations within architecture; methodological solutions were developed through design processes, representation, education and participation models.
Architecture Digitalization	Parametric_Design, Participatory Design, Digital_Integration, Generative_Design, Climate_Awareness	The integration of digital fabrication technologies into architectural processes is analyzed, including parametric design, BIM, algorithmic modeling, and administrative digitalization. Sustainability in education, climate-focused planning, and interdisciplinary ecological approaches are discussed alongside digital and pedagogical models.
Case Studies Addressing Three Themes Holistically	Bim_Integration, Interdisc_Teamwork, AI_Based_Workflow, Green Design	It includes studies based on production environments and case studies, where the themes of architecture, digital production and interdisciplinarity are addressed simultaneously.
Interdisciplinarity (Theoretical Approach)	Systems_Thinking, Interdisc_Teamscience, Ecology_Framework, User_Centered_Approach	The theoretical dimensions of interdisciplinarity were discussed through systems theory, collaboration models, ecological integrity and social science perspectives.

Table 4. Co-occurance matrix based on the intersection status of sub-themes

BIM-INT
(Bim_Integration) | ID-TWK
(Interdisc_Teamwork) | AI-WFL
(AI_Based_Workflow) | DIG TWN
(Digital_Twin) | PAR-DSN
(Parametric_Design) | MTV-ENV
(Metaverse_Environment) | DIG-INT
(Digital_Integration) | SYS-THK
(Systems_Thinking) | STN-EDU
(Sustainability_In_Education) | STD-INT
(Studio_Integration)
CRD-PRC
(Cross_Discipline_Practice) | GRN-DSN
(Green_Design) | CLM-AWR
(Climate_Awareness) | EDU-MDL
(Education_Model) | ECO-FRM
(Ecology_Framework) | SYS-ARC
(System_Architecture) | PTR-DSN
(Participatory_Design) | GEN-DSN
(Generative_Design) | ID-TSC
(Interdisc_Teamscience) | UCA-APP
(User_Centered_Approach)

Sub-Themes	BIM-INT	ID-TWK	AI-WFL	DIG-TWN	PAR-DSN	MTV-ENV	DIG-INT	SYS-THK	STN-EDU	STD-INT	CRD-PRC	GRN-DSN	CLM-AWR	EDU-MDL	ECO-FRM	SYS-ARC	PRT-DSN	GEN-DSN	ID-TSC	UCA-APP
BIM-INT	0	9	5	15	10	5	8	5	7	15	8	11	9	9	5	14	6	3	12	7
ID-TWK	9	0	8	7	8	6	5	8	7	12	7	9	9	7	5	3	12	2	13	8
AI-WFL	5	8	0	6	5	7	6	5	5	7	9	9	8	7	3	9	6	4	6	3
DIG-TWN	11	7	6	0	6	4	11	9	10	6	10	10	8	6	8	3	3	2	3	5
PAR-DSN	10	8	5	6	0	9	8	5	6	11	5	10	8	6	3	2	1	6	0	1
MTV-ENV	5	6	7	4	9	0	6	5	5	9	6	9	4	3	2	1	1	1	1	0
DIG-INT	8	5	6	11	8	6	0	8	9	8	9	7	7	4	6	15	8	7	10	3
SYS-THK	5	8	5	9	5	5	8	0	2	1	15	4	4	4	9	11	4	2	10	5
STN-EDU	7	7	5	10	6	5	9	2	0	6	4	4	6	5	6	4	2	1	3	1
STD-INT	11	12	7	6	11	9	8	1	6	0	5	2	3	5	9	12	10	6	9	12
CRD-PRC	8	7	9	10	5	6	9	15	4	5	0	8	6	7	3	6	9	2	2	3
GRN-DSN	11	9	9	10	10	9	7	4	4	2	8	0	3	2	2	4	3	1	2	1
CLM-AWR	9	9	8	8	8	4	7	4	6	3	6	3	0	1	2	1	1	4	2	1
EDU-MDL	9	7	7	6	6	3	4	4	5	5	7	2	1	0	1	5	10	0	2	4
ECO-FRM	5	5	3	8	3	2	6	9	6	9	3	2	2	1	0	4	4	0	4	3
SYS-ARC	14	4	9	3	2	1	15	11	4	12	6	4	1	5	4	0	2	2	3	2
PRT-DSN	6	12	6	3	1	1	8	4	2	10	9	3	1	10	4	2	0	2	7	9
GEN-DSN	3	2	4	2	6	1	7	2	1	6	2	1	4	0	0	2	2	0	2	1
ID-TSC	12	13	6	3	0	1	10	10	3	9	2	2	2	2	4	3	7	2	0	2
UCA-APP	7	8	3	5	1	0	3	5	1	12	3	1	1	4	3	2	9	1	2	0

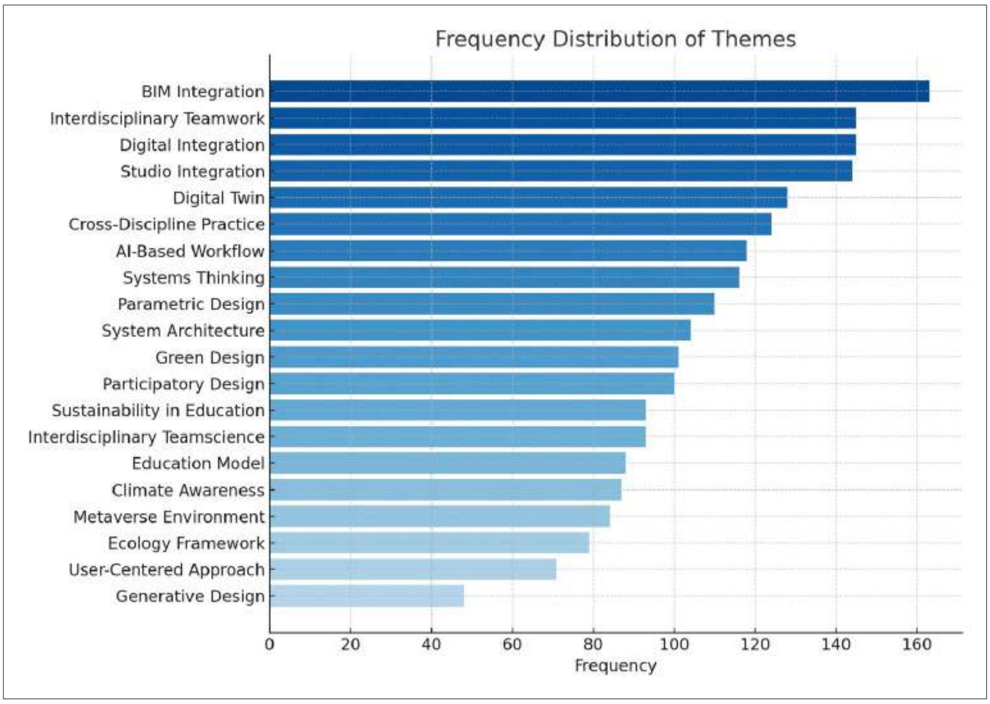

Figure 3. Individual frequency distribution of thematic codes (Designed by the Authors).

been reorganized to show the individual frequencies of the total 20 thematic codes defined in the content analysis.

The frequency distribution presented in the graph shows that the prominent themes in the context of digitalization and interdisciplinarity in architectural offices are particularly concentrated on the axes of BIM integration, interdisciplinary teamwork and digital integration. Furthermore, the high representation of themes such as studio integration, digital twins, cross-disciplinary practices, and AI-based workflows indicates that data- driven decision-making and parametric/computational design approaches are increasingly being systematically integrated into institutional design processes. These findings, obtained through the frequency of representation of these themes, allow for the holistic structuring of the content framework for the evaluation criteria to be used in the subsequent case studies.

FINDINGS

Synthesis of Content Analysis Findings

The thematic pattern presented in Figure 4 visualizes the integrated structure of the content analysis and reveals both the representational intensity of the themes in the literature and the structural relationships they establish with one another. The visual illustrates that the studies cluster within a multilayered interaction across the axes of digitalization, interdisciplinarity, and design, demonstrating that these conceptual domains have converged into a shared framework within the contemporary production practices of architectural offices. Two primary data sources were used in constructing this pattern. First, the single-frequency analysis identified the level at which each theme is represented in the literature, thereby producing an objective distribution of the intensity of approaches within the dataset. In the second stage, the co-occurrence matrix uncovered the relationships between the themes and revealed which concepts are positioned together and which diverge. Thus, the themes were validated not only through their visibility levels but also through their relational structures, resulting in the multilayered context that forms the basis of the thematic map presented in Figure 4.

Through this integrated analysis, Participatory Design, Interdisciplinary Teamwork, and the Ecology Framework were structured as three core themes that provide an analytical backbone due to both their differing levels of representation and their relational positioning. This triad brings together the high-, medium-, and low-visibility levels of the literature within a single framework, integrates the relational tendencies that explain thematic clustering, and grounds the theoretical model developed for architectural offices in a multidimensional conceptual depth (Figure 4).

The themes within the thematic pattern, beyond their definitions in the literature, were examined through case studies to determine the extent to which they are reflected in architectural design practice and the methods employed. The tools and responses these themes provide in architectural offices, and ultimately their impact on current interdisciplinary digitalization trends, are crucial for defining and evaluating the transition between theory and practice in the literature.

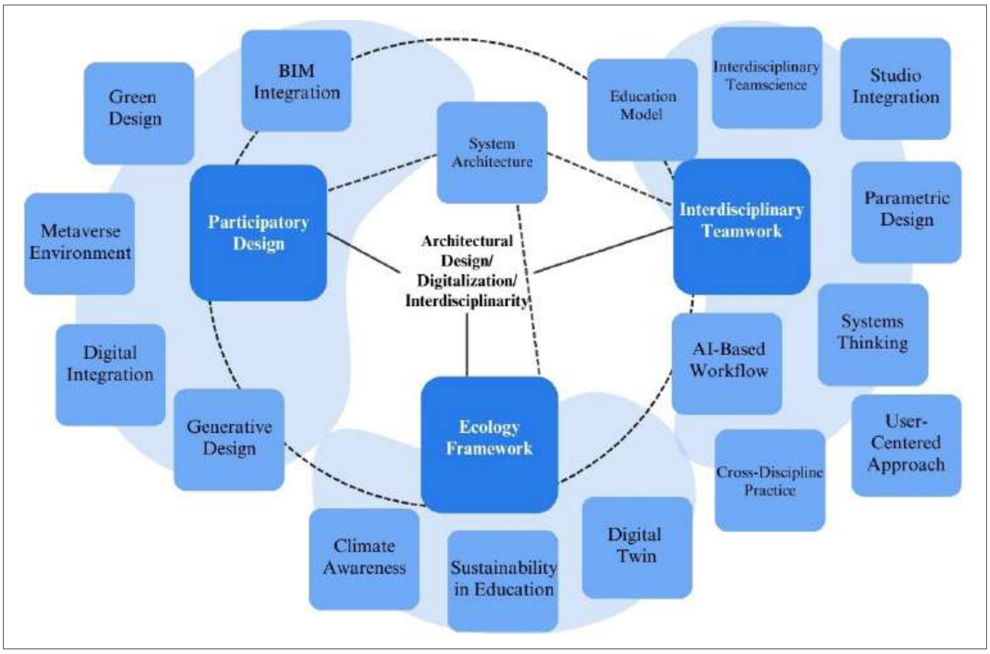

Figure 4. Thematic pattern of results based on content analysis (Designed by the Authors).

In the case selection process, the determining criteria were the architectural offices' ability to produce diverse design outputs at both national and international scales, their adoption of a digital production culture, and their implementation of interdisciplinary approaches within their organizational structures. The selected cases were analyzed on the basis of a Europe–Türkiye comparison, with Europe regarded as a pioneering geography where architectural and design practices are addressed holistically within a sustainable and interdisciplinary framework, supported by strategic programs such as Horizon Europe and the United Nations Sustainable Development Goals. Within the scope of the study, BIG, MVRDV, and Herzog & de Meuron from Europe, and Tabanlıoğlu Architects, GAD Architecture, and Erginoğlu & Çalışlar Architects from Türkiye were selected for the sample due to their effective use of digital design tools, their interdisciplinary collaborations, and their integration of sustainable design approaches into their projects. These offices stand out with their projects implemented across different geographies and their institutional identities that integrate local and global design approaches.

Architecture Offices in Europe and Interdisciplinary Design Approaches

The Europe-based offices examined in this study—BIG (Bjarke Ingels Group), MVRDV, and Herzog & de Meuron—are institutional structures that stand out internationally for their effective use of digital production technologies and their interdisciplinary design approaches.

The literature on BIG describes the offices "engineered without engines" approach as an ecological and interdisciplinary production model that transforms climatic data into a fundamental driver of form (Ingels, 2013). In projects such as the Shenzhen International Energy Mansion and West 57, environmental data becomes an operative core directly shaping mass morphology; this requires the early integration of performance design with engineering, material, and environmental simulation teams (Ingels, 2013). The Superkilen project reveals hybrid participatory practices in which representation and identity are foregrounded, yet decision-making authority remains concentrated among professional actors (Iborra Pallarés & Capdevila Castellanos, 2016). Productions such as Yes Is More and Hot to Cold strengthen the offices interdisciplinary organization by integrating digital representation, graphics, media, and user movement into the design process (Balık, 2017). As seen in 8 House, The Mountain, and Urban Rigger, programming becomes a dynamic tool simultaneously processing context, user behavior, and ecological requirements (Redyantanu, 2025). The office's open-studio structure, model–digital model cycles, and climate-scenario simulations form a horizontal production ecosystem in which all processes operate concurrently. In The Twist, Rhino–Grasshopper–based rule sets enable simultaneous optimization of structure and geometry, establishing a high-precision coordination between digital production and engineering (Margnelli & Tibuzzi, 2024).

MVRDV's production model is built upon synchronized data flows between MVRDV NEXT, The Why Factory, and the Modelmaking Lab. Density maps, microclimate simulations, and carbon calculations are integrated into parametric platforms at the early design stage; the co-design clusters bring together engineering, landscape, data analytics, and municipal technical teams within a shared decision-making environment. Digital tools are matched with user profiles and program scenarios, shifting participation to the early phases of design. The ecological framework is shaped through LIDAR-based topography, heat island models, solar–wind simulations, and LCA calculations (Tempestini, 2025). The Why Factory's "datascape" approach—seen in projects such as Pig City, Skycar City, Vertical Village, and What-If Nederland 2100—makes data-intensive design processes and multi- actor interactions visible (Yücel & Bekdaş, 2025). Tools such as RoofScape and Village-Maker provide interactive platforms where users can experience typology variations in a digital environment. The "nature-based stacking" approach reorganizes pixelated masses, topography, and natural layers through an ecology-oriented logic centered on diversity (Van Rooyen, 2022).

Herzog & de Meuron's methodology is built upon a hybrid structure that integrates the offices analog model culture with DTG's parametric modeling, scripting, and BIM-based geometric management. In projects such as Stamford Bridge and Tate Modern TM2, parametrically controlled systems—where each brick becomes a data point—strengthen the digital–physical prototyping cycle. The design process operates through a multi-actor negotiation model that foregrounds phenomenological parameters such as material behavior, atmosphere, light refraction, and tactility in the early stages. Dominus Winery and the Ricola Warehouse exemplify ecological and interdisciplinary production models in which material, climate, and construction techniques are interpreted simultaneously. The office's model room functions as a multi-scalar experimental environment where digital simulations are cross-validated with physical samples. In the Elbphilharmonie, topological acoustic panels are produced iteratively through digital analysis, CNC prototyping, and resonance testing. As Quesada-García notes, biomorphic material scans—fiber orientations and crystalline structures—are directly transferred into structural and surface geometries, illustrating a deeply interdisciplinary production culture.

The dynamics of the offices' technical and organizational processes were structured in relation to the themes identified through the analyses (Table 5).

BIG, integrates parametric simulations, VR-based user feedback, and performance data into a single design core, transforming the form-climate-user relationship into a dynamic system. MVRDV integrates extensive datasets, from LIDAR scans to density models, into its scenario engines through its "datascape" and "diagrammatic practice" approaches, transforming the design process into a plural production environment where urban, ecological, and programmatic layers can be simultaneously interpreted. Meanwhile, Herzog & de Meuron, with its hybrid digital- analog prototyping cycle led by the Digital Technology Group, activates micro-scale performance parameters such as material behavior, surface haptic, light refraction, and acoustic resonance in the early stages of design. When these three approaches are considered together, offices are being redefined through user experience, ecological data analytics, and multi-actor technical negotiation mechanisms.

Architectural Offices and Interdisciplinary Design Approaches in Türkiye

Within the scope of the study, the Türkiye-based offices Tabanlıoğlu Architects, GAD Architecture, and Erginoğlu & Çalışlar Architects were evaluated based on their engagement with digitalization and interdisciplinarity across different scales and design contexts, both nationally and internationally.

Tabanlıoğlu Architects operates with an integrated decision-making model in which participatory design, interdisciplinary digital integration, and ecological considerations function as a unified framework. In Teknopark Istanbul, user, investor, and management data were transformed into active design inputs through joint workshops, scenario modeling, and flow diagrams; spaces were reconceptualized as interfaces mediating the production cultures of different actors (Aydın, 2023). In the Atatürk Cultural Center (AKM), acoustic, structural, and stage technology teams worked as co-equal actors within a shared BIM-based model; the acoustic shell, balcony configuration, and volumetric decisions were defined through iterative comparisons of multilayered simulations (İlkhan Söylemez, 2022). The conversion of laser-scan and photogrammetry data into a digital twin, combined with CNC prototyping and full-scale material tests, enabled acoustic and lighting behavior to be directly integrated into material decisions (Özel, 2011).

In GAD Architects, parametric modeling, performance simulations, and user data constitute a simultaneously operating iterative computational ecosystem (Ertuğrul & Altın, 2022). GAD Lab transforms architectural practice into computational knowledge production by integrating software development, simulation, and advanced geometries; some projects are produced entirely through software-based workflows (Özcan, 2011). In Andalus Villa and GADtown, cellular automata and environmental inputs shape form through evolutionary processes, while Bulgur Palais re-generated topography- and culture-based geometries using new computational tools (Özcan, 2011). Participation is articulated through the early integration of field data and user density into the digital model, and ecological optimization is supported through material and microclimate testing (Ertuğrul & Altın, 2022).

Erginoğlu & Çalışlar Architects adopts a performance-driven model that integrates function, materiality, and environmental performance through digital analyses (Kurnalı, 2025). Its multi-actor negotiation system transforms daylight, thermal control, and usage scenarios into concurrent

Table 5. Evaluation of selected examples from europe on the axis of interdisciplinarity and digitalization

Related Themes	BIG	MVRDV	Herzog & de Meuron
User Centered Approach Participatory Design BIM Integration Parametric Design Digital Integration Systems Thinking	Collects user data using VR, GPS heat maps, and climate behavior maps; this data is linked to Grasshopper-based behavior simulations to determine form-decision relationships. The BIM model modifies scenarios in real time based on user flow.	Feeds LIDAR scans, social data, and density analytics into the MVRDV NEXT datascope system, where user profiles are matched to spatial typologies to perform variation tests.	Collects user data through phenomenological measurements of light, odor, acoustics, and surface contact; atmospheric decisions are structured by data based on sensory experience.
BIM Integration User Centered Approach Parametric Design Digital Twin AI Based Workflow	Automatically incorporates user feedback into the BIM model, enabling mass re-optimization for sun, wind, and shade scenarios. The design is constantly updated based on data.	User input is fed into the scenario engine; behavior data directly changes program decisions, and the design is continuously tested with digital variations.	User feedback is evaluated through material–light–acoustic performance tests; decisions such as surface transmittance, density, and light refraction are shaped by this testing cycle.
Interdisciplinary Teamwork Cross-Discipline Practice Interdisciplinary Teamscience Digital Integration	Project Room model enables municipal technical teams, engineers, and community representatives to work simultaneously on the same parametric model.	Co-design clusters structure combines the municipality–data analyst–landscape–architect interaction into a single diagrammatic decision environment; each actor's input layer is transparent.	The architect, acoustician, material scientist and structural engineer work around the physical model without hierarchy, simultaneously negotiating the design.
Participatory Design User-Centered Approach Parametric Design Digital Integration	VR-based feedback transforms parametric variable panels and digital user scenarios into an engagement tool.	Tools such as VillageMaker and RoofScape allow the user to experimentally produce their own typology.	Prioritizes sensory prototyping experience over digital engagement; user feedback is gathered through physical testing.
Parametric Design Digital Integration Ecology Framework Climate Awareness Green Design	They connect energy, wind, shade, and passive climate simulations to a single parametric kernel; mass automatically updates with changing parameters.	NEXT integrates topography, density, heat island and carbon data into a single model.	Considers material behavior (light scattering, permeability, heat accumulation) as the main input for ecological performance.
Ecology Framework Climate Awareness Green Design Parametric Design Digital Integration	Tests sunshade mock-ups, passive ventilation surfaces and roof landscaping with prototypes.	Validates digital microclimate scenarios with wind tunnel, light chamber and topographic models.	Conducts ecological performance tests such as light refraction, resonance, and heat storage on 1:1 material panel.
Green Design Ecology Framework Parametric Design Climate Awareness Digital Integration	Cutting optimization manages modular systems and the use of recycled materials with parametric calculations.	It embeds LCA calculations into the design scenario engine; material selection is determined by carbon footprint.	Material is judged based on fiber direction, density and permeability tests; ecological performance is the main criterion.
Digital Integration BIM Integration Parametric Design Digital Twin	It integrates the BIM–Grasshopper–simulation trio.	MVRDV NEXT connects all data layers to a script-based processing system.	It combines point cloud, script, CNC and BIM in one flow via DTG.
Interdisciplinary Teamwork Interdisciplinary Teamscience Cross-Discipline Practice	With horizontal organization, it operates all expert groups in a single cycle	It establishes a tripartite structure that puts research–digital model–physical model in a continuous loop.	Brings together different experts in the same volume with a non-hierarchical team-science organization.
Digital Integration Interdisciplinary Teamwork Systems Thinking	Establishes a digital variation–model–simulation–revision cycle.	Progresses cyclically as diagram–scenario–model–data analysis.	Uses the 1:1 panel–performance test–CNC update cycle.

decision-making inputs; material selections are aligned with energy consumption and microclimatic effects. In the Palanga project, compacted earth walls, nail- less timber structures, passive stack ventilation, and microclimate strategies embedded into the topography produce an ecological construction model grounded in local techniques (Kariptaş & Kariptaş, 2025).

The dynamics of the offices technical and organizational processes were structured in relation to the themes derived from the analyses (Table 6).

Tabanlıoğlu Architects integrates digital design processes with a focus on sustainability and spatial quality in large-scale mixed-use projects and public buildings. GAD Architects supports its innovative design pursuits with digital production technologies and AI-based analysis, developing flexible design processes based on collaboration with experts from various disciplines. Erginoğlu & Çalışlar Architects combines local context and cultural values with contemporary architectural language, producing environmentally sensitive projects using digital design tools and sustainable materials.

Synthesis: Comparison of Examples of Architectural Offices in Europe and Türkiye Based on Digital

Table 6. Evaluation of selected examples from Türkiye on the axis of interdisciplinarity and digitalization

Related Themes	Tabanlıoğlu Architects	GAD Architects	Erginoğlu & Çalışlar Architects
User-Centered Approach Participatory Design Parametric Design Digital Integration Climate Awareness Ecology Framework Systems Thinking	User profiles, investor expectations, and operational flows are collected through hot-desk meetings, scenario testing, and usage flow diagrams; data is transformed into live inputs that are constantly updated.	User density, behavioral patterns, and field observations are directly linked to the parametric model; the data redefines the form with each iteration.	User needs are evaluated together with the social-cultural context; behavioral data is integrated into daylight, ventilation and plan typology analyses.
User-Centered Approach Participatory Design Climate Awareness Ecology Framework	Common areas and circulation decisions are repeatedly revised according to user practices; the design program is shaped by multi-actor negotiations.	User inputs directly produce variation in performance scenarios; the model is constantly recalibrated based on environmental and social data.	User behavior is evaluated simultaneously with interior organization and climatic strategies; the digital model is updated with user data.
Interdisciplinary Teamwork Interdisciplinary Teamscience BIM Integration Digital Integration Parametric Design	At AKM, acoustics, structural, stage technology and conservation teams work as peers around a BIM-based common model; decisions mature through an iterative negotiation process.	Parametric design, data processing, software development, and materials research proceed through parallel task-sharing; all actors feed into the same model.	Engineering, material, landscape and user representatives meet on a common platform at the early stage; multi-actor negotiation creates the decision chain.
Digital Twin BIM Integration Participatory Design	Laser scanning, photogrammetry and digital twin models make expert feedback visible; the BIM platform acts as a technical engagement tool.	VR-based feedback, parametric variable panels, and density analyses transform digital participation into active design input.	Digital tools enable participation through performance testing; field observation and digital verification go hand in hand.
Climate Awareness Green Design Parametric Design	Wind, shadow, heat island, courtyard morphology and permeable façade scenarios determine the mass organization as initial design input.	Material behavior, light transmittance, thermal performance and microclimate data are integrated with parametric control layers; the form is reshaped with ecological performance.	Digital models are built simultaneously with climatic data; environmental analyses define the performance infrastructure.
Green Design Ecology Framework Digital Integration	Performance is verified by testing acoustic panels, ceiling sections and facade surfaces in models close to 1:1.	Sun-shade surfaces, passive ventilation elements and roof landscaping are tested with hybrid (digital + physical) prototypes.	Compressed earth walls, horasan mixtures and wooden purlin-rafter system are tested in the field and turned into an ecological prototype.

Table 6. Continue

Related Themes	Tabanlıoğlu Architects	GAD Architects	Erginoğlu & Çalışlar Architects
Ecology Framework Green Design Parametric Design	Glass-ceramic blended modules are tested with digital optimization at the material level according to light transmittance, thermal mass and energy behavior.	Recycled material, cutting optimization and performance data are managed within the parametric system.	Materials are selected based on their maintenance cycle, microclimate impact and performance in relation to local techniques.
Digital Twin BIM Integration Parametric Design Climate Awareness	Digital twin, laser scanning, photogrammetry, BIM integration creates a common platform for both analysis and design.	BIM–Grasshopper–script-based variation generation–simulation infrastructure merges into a single computational backbone.	Digital models that combine daylight, airflow, heat and structural analysis are established at an early stage.
Interdisciplinary Teamwork Digital Integration	During the AKM construction process, different technical teams work on the same model without a hierarchy; the organization is based on a simultaneous negotiation system.	Parallel teams of architects, engineers, software developers and materials researchers carry out synchronized production.	Engineering, materials, landscape and user teams meet on a single platform at an early stage; decisions are shaped by collective production.
BIM Integration Ecology Framework	Acoustic simulation, structural analysis and scene scenarios are constantly compared with the BIM model, establishing an iterative loop of information integration.	The digital variation–mock–performance test–revision cycle forms the computational core of the design.	A cyclical flow of information is established between usage scenarios, climatic data and plan typologies; design progresses according to performance.

Production and Interdisciplinary Design Approaches

A holistic reading of the European (BIG, MVRDV, Herzog & de Meuron) and Türkiye (Tabanlıoğlu, GAD, Erginoğlu & Çalışlar) cases demonstrates that the emphases on interdisciplinarity and digitalization take shape with varying intensities across the two contexts. Architectural offices in Europe adopt a highly integrated, data- driven, and iterative production approach in which processes—from user data collection to digital twin and BIM integration, from parametric variation generation to microclimate testing—are supported by both computational tools and physical prototypes. While BIG and MVRDV link user behavior, topographic information, density analytics, and climate scenarios to a single parametric core, Herzog & de Meuron foregrounds phenomenological measurements and material behavior as primary inputs shaping ecological performance.

In contrast, within the Türkiye context, although the transfer of data and participatory processes into design is strong, team organization and digital infrastructure integration tend to operate more at the scale of individual projects and through platform-based, multi-actor models. Tabanlıoğlu's multi-actor negotiation systems, GAD's incorporation of field data into parametric control layers, and Erginoğlu & Çalışlar's site-oriented approach that transforms local material–microclimate relations into ecological prototypes collectively indicate that participation and ecological sensitivity are strong in Türkiye offices, yet computational cycles are not as deeply integrated as in the European examples.

Across both geographies, a shared tendency is the emergence of a triad—user data + environmental data + material performance—as a progressively decisive core in early design stages. However, the European context reinforces this core through digital twin workflows, script-based processing, and high-resolution performance testing, whereas the Türkiye context deepens it through local contextualization, physical prototyping, and multi-actor negotiation. The comparative evaluations developed to analyze the thematic approaches of European and Türkiye offices are presented in Table 7.

In Europe-based offices, the culture of digital production and interdisciplinary organization appears to have evolved into an integrated and institutionalized structure in which parametric modeling, BIM, and AI-based optimization tools are embedded from the early stages of design. In the Türkiye examples, however, these approaches tend to concentrate more at the project scale and within specific domains such as energy efficiency, performance analysis, and spatial organization, while the use of artificial intelligence and advanced digital production tools remains comparatively limited. This

Table 7. Comparison of European and Türkiye examples based on digital production and interdisciplinary design approaches

Related Themes	European Context (BIG – MVRDV – H&dM)	Türkiye Context (Tabanlıoğlu – GAD – E&C)
User-Centered Approach	User behavior data is collected in high resolution using digital tools (VR, GPS, LIDAR, sensory measurements). The data is directly linked to the model and guides the design.	User inputs are collected through the social-cultural context and field observations. There is integration with the model, but the digital data density is not as high as in Europe.
Participatory Design	Participation takes place in digital environments; users are directly involved in variation production. At H&dM, the sensory prototype experience is at the forefront.	Participation is mostly conducted through joint table meetings, negotiations, and field-based actor interactions; a hybrid structure prevails.
BIM Integration	It is tightly integrated with BIM, simulation, digital twins, and performance models.	The BIM common model ensures multi-actor equality; integration is strong, but data density is more limited compared to Europe.
Parametric Design	The parametric kernel comprehensively handles climate, density, user flow, and topography.	Parametric decisions combine field data, interior organization, and performance analysis.
Digital Integration	Script-based processing, automatic transfer of data sets, and digital twin flows are highly integrated.	Digital models are established early on; field data and prototypes are processed simultaneously.
Digital Twin	Point cloud, laser scanning, and physical test data are integrated with the digital twin.	The combination of digital twin + photogrammetry + BIM offers a common platform.
AI-Based Workflow	Data-driven automation and scenario engines approach AI-based flows.	AI-based flows are limited; more parametric and data-driven systems are implemented.
Interdisciplinary Teamwork	Highly disciplined teams work simultaneously and transparently on a shared model.	Technical teams come together early on; the BIM model supports equal representation.
Interdisciplinary Teamscience	The findings show that teams synchronize communication through shared workspaces while bringing together different areas of expertise within the same production cycle, establish information integration through digital integration and prototyping feedback loops, and conduct decision-making processes through iterative negotiation rather than hierarchy.	It demonstrates that multidisciplinary expertise approaches equivalent representation, particularly in large and complex projects; communication and coordination are mostly established around common platforms such as BIM/digital twins; and information integration is achieved through project-based integration and parallel task sharing.
Cross-Discipline Practice	Architects, data analysts, landscape architects, and engineers interact in a single decision-making environment.	Software developers, engineers, and materials researchers come together on a single platform through parallel production.
Ecology Framework	It is verified by ecological performance tests; it is the primary input for the design.	Local materials, microclimate measurements, and ecological prototypes are decisive factors.
Climate Awareness	Climate data is linked to the parametric model at an early stage; it generates variation.	Sunlight, ventilation, and microclimate data are evaluated in parametric models.
Green Design	LCA, carbon footprint, and energy analyses are important.	Local materials, recycling, and field-tested prototypes are emphasized.
Systems Thinking	A circular flow is established between data, performance, and environmental inputs.	A circular flow of information is created between the usage scenario, climate data, and plan typology.
Studio Integration	In-house production is structured around studio–laboratory continuity. The digital model–physical model/prototype cycle is carried out simultaneously in the same production environment, allowing decisions to be refined iteratively.	Studio integration is primarily visible through task sharing between in-house R&D/computational production units and project teams.
Sustainability in Education	Data-driven scenario generation, ecological frameworks, and climate modeling institutionalize a learning system through which research outputs inform project decisions.	Sustainability knowledge is mostly generated through environmental analyses, material performance, and field-validated ecological prototypes within the project workflow and shared across teams.

Table 7. Continue

Related Themes	European Context (BIG – MVRDV – H&dM)	Türkiye Context (Tabanlıoğlu – GAD – E&C)
Metaverse Environment	Metaverse/immersive environments appear in the literature more as a secondary layer in the context of the expansion of digital representation and interactive decision environments.	The metaverse environment theme is represented in a limited way; digital participation and interaction are established on a project basis, mostly through tools such as VR-based feedback/parametric variation panels, and are not discussed in the context of an institutionalized plane as a continuous metaverse ecosystem.
Generative Design	Generative design functions as a mechanism that feeds early-stage option generation through script/parametric rule sets and scenario engines; data-scenario-based variation generation at MVRDV and the derivation of mass decisions using Grasshopper-based behavior/climate inputs at BIG demonstrate how generative logic is tied to the design core.	Computational models, software-based manufacturing, and approaches where form is derived evolutionarily through environmental inputs (e.g., cellular automata and project-specific computational manufacturing) are highlighted. In Tabanlıoğlu and E&C, however, generative logic, parametric control layers, and performance scenarios come into play in a more selective/project-focused manner.

indicates that, whereas participation and collaboration in European offices are systematically organized through digital models, similar processes in Türkiye are structured in a more contextual and project-based manner.

DISCUSSION: ANALYTICAL INFERENCES

In the 21st century, architectural design has become intertwined with digital production technologies that develop on the basis of interdisciplinarity, and this multilayeredness has become a necessary design approach. New design paradigms have transformed both the organizational structure and production processes of architectural offices, paving the way for the emergence of multilayered, holistic, and flexible design models. The findings of this study demonstrate that digitalization in 21st-century architectural offices is a holistic restructuring process that has radically transformed production culture, decision-making dynamics, and inter-actor interactions through interdisciplinary processes.

The comparative analyses of the European (BIG, MVRDV, Herzog & de Meuron) and Türkiye (Tabanlıoğlu, GAD, Erginoğlu & Çalışlar) cases demonstrate that contemporary architectural offices are restructuring their design processes around three fundamental axes: (1) data-driven participatory design, (2) computational–interdisciplinary integration, and (3) the embedding of ecological performance into the early stages of design. The European examples presented in the tables—BIG, MVRDV, and H&dM—have developed a high-intensity participation model in which user data are collected through VR, LIDAR, GPS behavior maps, and sensory measurement protocols, and design variations are generated through real-time digital scenarios. In Türkiye, Tabanlıoğlu, GAD, and Erginoğlu & Çalışlar operate through multi-actor negotiation systems that integrate user input primarily with programmatic, climatic, structural, and local behavioral data. However, whether this backbone transforms into an "enterprise pipeline" in production represents a critical threshold. In European examples, standardizing script-based variation, simulation, and prototyping cycles as a repetitive workflow transforms tools from a project-specific repertoire into enterprise capacity. In Turkish examples, while digital twin, BIM common model, and hybrid prototyping practices are strong, the fact that these components often operate as a system that is rescaled according to project requirements and configured according to context produces institutionalization on a more selective and situation-specific plane.

In this study, the European and Turkish cases examined reveal the contextual differences in how digitalization reshapes the design process. In Europe, BIG, MVRDV, and Herzog & de Meuron turn digitalization into the computational backbone of design by integrating data collection techniques—such as VR-based behavioral mapping, LIDAR, GPS density measurements, and sensory protocols—with script-based variation systems and high-resolution performance simulations within a single operational loop. In contrast, in Türkiye, Tabanlıoğlu Mimarlık, GAD Architecture, and Erginoğlu & Çalışlar employ digitalization more as a project-based toolkit that varies according to contextual requirements, developing methods such as BIM-based shared models, digital twin integration, parametric geometry, and hybrid prototype production in ways that focus on energy efficiency, climatic performance, and spatial organization problems. When these two contexts are compared, it becomes evident that the European cases have transformed high-intensity data flows and script-based computational decision chains into an institutional production culture, whereas the Turkish cases have adopted a more flexible and situation-specific model of digital production by associating digital tools with local context, multi-actor negotiation, and field-based ecological validation. Therefore, although digitalization functions as a guiding component of design in both contexts, its scale of implementation, computational depth, and level of institutionalization differ according to context. The key factor that makes the difference at this point is whether technology is positioned as a tool that reduces uncertainty in the early design phase or as a flexible space that is continuously recalibrated with contextual data. This positioning directly affects at which stage and with what role distribution BIM and AI-based tools will be included in the process.

In the Turkish cases, the concentration of digital approaches in specific areas such as energy efficiency, performance analysis, and spatial organization may be associated not only with the fact that these domains are more conducive to justifying design decisions through measurable short-term indicators, but also with their capacity to generate a shared consensus among project stakeholders. When performance analysis and energy efficiency are addressed together with BIM-based coordination, they constitute the layers of design that can be managed with the lowest degree of uncertainty in terms of both technical verification and implementation coordination. For this reason, the areas in which the return on investment of digitalization becomes visible most rapidly tend to cluster around these themes. This becomes particularly evident in the cases of Tabanlıoğlu, GAD, and Erginoğlu & Çalışlar, where concepts such as digital twins, shared models, and parametric modeling are deployed strategically არა at the earliest stage of design, but rather to verify performance and maintain the consistency of spatial organization.

The more limited use of AI-based optimization and advanced digital production technologies in Turkish architectural practice is related to whether the data flow and verification mechanisms required by optimization can be sustained at an institutional scale. AI-based option generation requires the translation of design goals into measurable criteria, the maintenance of data consistency, and the definition of how the generated variations will be linked to the hierarchy of design decisions. When this connection is not established, optimization outputs may remain as supportive secondary components at particular stages rather than becoming lasting decision inputs within the design process. In this context, the critical threshold for the broader adoption of these technologies lies in the definition of target functions, the continuity of data, and the way decision responsibility is distributed within the design team.

The barriers that prevent the embedding of BIM- and AI-based tools into the early stages of design become concrete in the tension between uncertainty and the data clarity demanded by the model. When uncertainty is intended to be preserved in early design as a driving force for creative exploration and alternative generation, the premature structuring of the model may pose risks; this, in turn, makes it difficult for BIM and automation-based decision chains to function as the backbone of design from the outset. In the European cases, the operation of data collection protocols—such as VR, LIDAR, and GPS—as a systematic framework that feeds option generation in the early stages provides a form of feedback that reduces uncertainty, whereas in the Turkish cases the early stage is often positioned as a phase in which contextual negotiation predominates and the model serves to carry decisions only once they have become clearer. For this reason, the decisive threshold in early-stage integration is less a matter of modeling capacity than of process consensus regarding which tools will be used to manage uncertainty, and at what stage.

Organizational culture, project procurement models, professional competencies, and market conditions should be considered together as the broader framework in which these differences become visible. Standardized digital workflows at the institutional scale require the continuity of interdisciplinary teams, the stability of role definitions, and the documentation of organizational learning. When these conditions are met, digitalization can move beyond being a project-specific toolkit and become an institutional and educational capacity. Conversely, in environments where project procurement models encourage fragmented service production, delivery schedules are compressed, and the balance between fees and performance is fragile, offices may tend to concentrate their digital investments in more goal-oriented areas. Within this framework, the difference between the institutionalized processes observed in the European cases and the contextual, project-based flexibility that stands out in the Turkish cases depends on the risk conditions under which offices position digitalization and the logic of return through which they evaluate it.

CONCLUSION: FUTURE PERSPECTIVES AND CONCEPTUAL EXPLANATIONS

In light of these findings, the future perspective suggests three core axes of transformation for architectural practice:

(i) Data-driven, multi-actor, iterative negotiation platforms that structure the design process;

(ii) Hybrid design ecologies that integrate computational modeling, software development, digital twins, and performance testing into a single loop;

(iii) Digital simulation models that unify material, climate, topography, and behavioral data within a shared performance backbone.

The findings demonstrate that digitalization and interdisciplinary design operate together in architecture offices across three concrete planes. On the first plane, BIM integration and digital integration emerge as the operational ground of interdisciplinary teamwork. The high frequencies and co-occurrence relations identified in the content analysis reveal that production settings in which coordination is established through a shared model occupy a central place in the literature. On the second plane, the pattern in which parametric design intersects with digital integration and systems thinking indicates that design decisions are produced through feedback-based loops rather than through isolated stages. This suggests that the decision-making process is expanded through multiple layers of data. On the third plane, the reading of ecology framework and climate awareness themes together with digital simulation and green design codes shows that environmental performance is positioned as one of the guiding inputs of design.

The comparative case reading demonstrates that these three planes correspond to different modes of organization in the European and Turkish contexts. In the European cases, digital workflows appear to generate a more continuous coordination structure from the early stages of design onward, whereas in the Turkish cases similar components are reconfigured according to project scale and contextual requirements. This finding analytically renders visible the study's distinction between institutionalized computational loops and project-based adaptive digitalization, suggesting that the transformation of digitalization into institutional capacity is associated less with the diversity of tools than with the level of continuity and integration within the workflow.

The practical counterpart of the first axis lies in the fact that participatory design does not remain at the level of isolated feedback, but is connected to the same chain of production as in-house interdisciplinary teamwork. The findings show that user-centered approach and participatory design themes become meaningful when read together with digital integration and interdisciplinary collaboration. For this reason, the function of multi-actor negotiation platforms is not merely to bring actors side by side, but to make transparent the inputs and tools through which design decisions are produced. Within the scope of the study, the themes of BIM integration and digital integration point to the shared infrastructures through which this transparency can be produced in practice.

The second axis clarifies how offices construct hybrid design ecologies. In the European cases, digital integration is seen to turn into a recurring loop together with script/parametric production, simulation logic, and prototyping culture, whereas in the Turkish cases BIM, parametric modeling, digital twins, and interdisciplinary collaboration mostly operate as a combination reconfigured according to project requirements. This finding is more explanatory when digitalization is evaluated not in terms of which tools exist, but in terms of how those tools are connected to one another. The themes of BIM integration, digital integration, parametric design, and interdisciplinary teamwork, which establish strong co-occurrence relations in the content analysis, constitute the core of this relationality.

The third axis brings the relationship established between ecology framework and climate awareness themes and digital production to the level of practice. The findings indicate that, in some cases, ecological parameters become determining inputs of the model in the early stages of design, while in other cases they enter the process mainly at the stages of verification or improvement. This differentiation can be explained by the fact that, in the European context, digital simulation is embedded earlier into the guiding backbone of design, whereas in the Turkish context ecological decisions advance more selectively in relation to local context, material conditions, and implementation constraints. Accordingly, the study demonstrates that the operationalization of ecological performance through digitalization is directly related to the stage at which interdisciplinary collaboration and data layers are connected to design.

The results generate implications for practitioners, educators, and policy makers. For practitioners, the continuity of interdisciplinary teamwork is strengthened under conditions in which digital integration ceases to be a project-based toolkit and becomes part of the culture of production. For educators, the intersection of studio integration and education model themes with digitalization and interdisciplinarity in the content analysis suggests that this field should be approached as a framework that teaches mechanisms of collaboration and representation. For policy makers, as indicated by the risk of tokenistic collaboration, ensuring that interdisciplinarity does not remain merely formal is related to the definition of data sharing, interoperability, and representational mechanisms within the process.

The limitation of the study lies in the fact that the findings are derived from the content analysis of 45 articles selected from the 2005–2025 period and from the comparative reading of office practices through data reported in secondary sources. While this framework systematically renders thematic patterns and conceptual relations visible, it is not intended to directly test causal explanations regarding the internal processes of offices, such as which institutional factors determine role distribution, decision hierarchies, or tool selection. In addition, since the content analysis approach reveals the intensities and co-occurrence patterns of themes represented in the literature, the results reflect the tendencies of practices that have a counterpart in the literature.

Future research may deepen the thematic framework established in this study. First, the same coding system can be reapplied to expanded samples across different geographies and different scales of practice (small, medium, and large offices) in order to compare the continuity and axes of differentiation in digitalization–interdisciplinarity patterns across contexts. Second, the criteria derived from the content analysis can be combined with primary data—such as in-office workflow documentation, project process records, and multi-actor coordination protocols—to analyze the organizational mechanisms that determine the level of institutionalization of digital integration. These two directions would strengthen the relationship between theory and practice in the study, while making it possible to discuss, on an empirical basis, how a digitalizing culture of production can be transformed into a sustainable capacity within architecture offices.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Altıntaş, L. E., Kaşalı, A., & Doğan, F. (2022). Multi-disciplinarity and collaboration in computational design teams. *Proceedings of eCAADe 40 – Co-creating the Future, 1*, 577–586. https://doi.org/10.52842/conf.ecaade.2022.1.577

Ashtari Talkhestani, B., Jung, T., Lindemann, B., Sahlab, N., Jazdi, N., Schloegl, W., & Weyrich, M. (2019). An architecture of an intelligent digital twin in a cyber-physical production system. *at-Automatisierungstechnik*, *67*(9), 762–782. https://doi.org/10.1515/auto-2019-0039

Awe, M., Malhi, A., Budka, M., Mavengere, N., & Dave, B. (2025). Towards 4D BIM: A systematic literature review on challenges, strategies and tools in leveraging AI with BIM. *Buildings*, *15*(7), 1072. https://doi.org/10.3390/buildings15071072

Aydın Aktaş, B. N. (2023). Designing a technology and innovation center in the context of Antalya/ Türkiye. *AURUM Journal of Engineering Systems and Architecture*, *7*(2), 145–163. https://doi.org/10.53600/ajesa.1208079

Badawi, A. M., & Abdullah, M. R. (2021). Interdisciplinary design education: Development of an elective course in architecture and engineering departments. *Journal of Engineering and Applied Science*, *68*, 1–13. https://doi.org/10.1186/s44147-021-00010-2

Balık, D. (2015). The contemporary architect as editor/curator: Yes Is More and Hot To Cold by BIG. *Bradaschia, M.*, *MVRDV four projects*. *IL PROGETTO*, *41*, 14–25.

Borgman, C. L. (2015). *Big data, little data, no data: Scholarship in the networked world*. MIT Press. https://doi.org/10.7551/mitpress/9963.001.0001

Broo, D. G., Bravo-Haro, M., & Schooling, J. (2022). Design and implementation of a smart infrastructure digital twin. *Automation in Construction*, *136*, 104171. https://doi.org/10.1016/j.autcon.2022.104171

Buchanan, R. (2019). Systems thinking and design thinking: The search for principles in the world we are making. *She Ji: The Journal of Design, Economics, and Innovation*, *5*(2), 85–104. https://doi.org/10.1016/j.sheji.2019.04.001

Butt, A. N., & Dimitrijević, B. (2022). Multidisciplinary and transdisciplinary collaboration in nature-based design of sustainable architecture and urbanism. *Sustainability*, *14*(16), 10339. https://doi.org/10.3390/su141610339

Chandler, D. (2004). *The sociology of knowledge: A reader*. Oxford: Blackwell Publishing.

Chettiparamb, A. (2007). *Interdisciplinarity: A literature review*. Southampton: University of Southampton.

Ertuğrul, Ü., & Altın, M. A. (2022). Sürdürülebilir tasarımda bir arayüz olarak iç mimarlık. *Online Journal of Art & Design*, *10*(1), 94–119.

Helmane, I., & Briška, I. (2017). Project-based learning and transdisciplinary approach in higher education. *Journal of Higher Education*, *68*(3), 321–335.

Iborra Pallarés, V., & Capdevila Castellanos, I. (2016). Public participation process as a tool for innovation in the design of public spaces: The case of Superkilen Park by Bjarke Ingels Group.

Ingels, B. (2013). Engineering without engines. *Volume*, *37*, 142.

İlkhan Söylemez, D. (2022). Brutalist architecture: Istanbul Atatürk Cultural Center [Brütalist mimari: İstanbul Atatürk Kültür Merkezi]. *Türk & İslam Dünyası Sosyal Araştırmalar Dergisi*, *9*(34), 214–223. https://doi.org/10.29228/TIDSAD.64355

Jin, S. (2024). Interdisciplinary perspective on architectural programming: Current status and future directions. *Engineering, Construction and Architectural Management*, *32*(11), 7332–7372. https://doi.org/10.1108/ECAM-04-2024-0408

Jutraž, A., & Zupančič, T. (2014). The role of architect in interdisciplinary collaborative design studios. *IGRA Ustvarjalnosti (IU)/Creativity Game (CG)–Theory and Practice of Spatial Planning*, *2*, 34–42. https://doi.org/10.15292/IU-CG.2014.02.034-042

Kauffman, S. (2016). *Humanity in a creative universe*. Oxford University Press.

Kariptaş, F., Aytıs, S., & Seçer Kariptaş, F. (2024). Design criteria of next generation offices. *Online Journal of Art and Design*, *12*(3), 188–197.

Kassem, M., & Ahmed, A. L. (2022). Digital transformation through building information modelling: Spanning the macro-micro divide. *Technological Forecasting and Social Change*, *184*, 122006. https://doi.org/10.1016/j.techfore.2022.122006

Klein, J. T. (1990). *Interdisciplinarity: History, theory, and* *practice*. Wayne State University Press.

Klein, J. T. (1996). Cross-disciplinary perspectives on the nature and scope of interdisciplinarity. *Annual Review of Sociology*, *22*, 8.

Knippers, J., Kropp, C., Menges, A., Sawodny, O., & Weiskopf, D. (2021). Integrative computational design and construction: Rethinking architecture digitally. *Civil Engineering Design*, *3*(4), 123–135. https://doi.org/10.1002/cend.202100027

Kuhn, T. (1962). *The structure of scientific revolutions*. University of Chicago Press.

Li, J., Liu, Z., Han, G., Demian, P., & Osmani, M. (2024). The relationship between artificial intelligence (AI) and building information modeling (BIM) technologies for sustainable building in the context of smart cities. *Sustainability (2071-1050)*, *16*(24), 10848. https://doi.org/10.3390/su162410848

Margnelli, A., & Tibuzzi, E. (2024). The twist: Blending art with architecture and engineering. *Technology | Architecture + Design*, *8*(2), 204–208. https://doi.org/10.1080/24751448.2024.2405378

McAlister, J. S., Blum, M. J., Bromberg, Y., Fefferman, N. H., He, Q., Lofgren, E., ... & Reed, J. M. (2025). An interdisciplinary perspective of the built-environment microbiome. *FEMS Microbiology Ecology*, *101*(1), fiae166. https://doi.org/10.1093/femsec/fiae166

Miao, C., Wang, H., Meng, X., Hou, X., Yan, Y., Liu, S., & He, Y. (2024). BIM-supported knowledge collaboration: A case study of a highway project in China. *Sustainability*, *16*(20), 9074. https://doi.org/10.3390/su16209074

Nicolescu, B. (1999). The transdisciplinary evolution of learning. In *Symposium on overcoming the underdevelopment of learning at the annual meeting of the American educational research association*, Montreal, Canada.

Nowotny, H., Scott, P., & Gibbons, M. (2001). *Re-thinking science: Knowledge and the public in an age of uncertainty*. Polity.

Shim, J. H., Ham, N. H., & Kim, J. J. (2024). Collaborative BIM-based construction coordination progress modeling using extended collaborative process modeling (exCPM). *Buildings*, *14*(2), 358. https://doi.org/10.3390/buildings14020358

Özel, F. (2011). *Global and local design identities: East meets West*. Arizona State University.

Özcan, N. (2011). Computational design techniques in architecture and examples from Turkey. [Mimarlıkta hesaplamalı tasarım teknikleri ve Türkiye örnekleri] [Master's Thesis]. Dokuz Eylul Universitesi.

Özkan Üstün, G., & Işıklar Bengi, S. (2021). A study on developing future scenarios in architectural design. *Periodica Polytechnica Architecture*, *52*(1), 75–84. https://doi.org/10.3311/PPar.14965

Pallarés, V. I., & Castellanos, I. C. (2016). *Public participation process as a tool for innovation in the design of public spaces: The case of Superkilen Park by Bjarke Ingels Group*. University of Alicante.

Peters, B. (2013). Realising the architectural idea: Computational design at Herzog & de Meuron. *Architectural Design*, *83*(2), 56–61. https://doi.org/10.1002/ad.1554

Phocas, M. C. (2015). Interdisciplinary technology-driven design processes in architecture. *Archi DOCT*, *3*(1), 10–19.

Piaget, J. (1973). *To understand is to invent: The future of education*. Grossman.

Pinter-Wollman, N., Penn, A., Theraulaz, G., & Fiore, S. M. (2018). Interdisciplinary approaches for uncovering the impacts of architecture on collective behaviour. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1753), 20170232. https://doi.org/10.1098/rstb.2017.0232

Qian, C., Liu, X., Ripley, C., Qian, M., Liang, F., & Yu, W. (2022). Digital twin—Cyber replica of physical things: Architecture, applications and future research directions. *Future Internet*, *14*(2), 64. https://doi.org/10.3390/fi14020064

Redyantanu, B. P. (2025). Integratıon, Relatıon, A,and Recreatıon: Rethınkıng Archıtectural Programmıng. *Journal of Architecture & Environment*, *24*(1), 15–32. https://doi.org/10.12962/j2355262x.v24i1.a22771

Repko, A. F. (2008). *Interdisciplinary research: Process and theory*. SAGE Publications.

Tebes, J. K., & Thai, N. D. (2018). Interdisciplinary team science and the public: Steps toward a participatory team science. *American Psychologist*, *73*(4), 549. https://doi.org/10.1037/amp0000281

Tempestini, M. (2025). Criticism goes social: Exploring public architectural criticism through architecture awards. *Archnet-IJAR: International Journal of Architectural Research*, *19*(2), 411–433.

Tosarello, M. (2024). *Design processes in BIG's offices.* Politecnico di Torino.

Van Rooyen, X. (2022). Free plan versus free rooms: Two conceptions of open architecture. *Footprint*, *16*(2), 85–104. https://doi.org/10.59490/FOOTPRINT.16.2.6093

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Yücel, A., & Bekdaş, H. D. (2025, June). Mapping the density, diversity, and digitization of the 21st century: The diagrammatic architecture of MVRDV. In *Proceedings of the international conference of contemporary affairs in architecture and urbanism-ICCAUA*, *8*(1), 138–146. https://doi.org/10.38027/ICCAUA2025EN0238