ARCHITECTURAL EPISODES 03:

INNOVATION, TECHNOLOGY, DIGITAL TRANSFORMATION AND THE FUTURE OF THE CONSTRUCTION INDUSTRY

INTERNATIONAL SYMPOSIUM

PROCEEDINGS BOOK

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Focus Theme

Industrial Revolution is considered an important turning point in human history, influenced technological developments, which inevitably continued over the years. The technological developments accelerate and progress in many industries and today it is still developing with new generation advanced technologies. Construction industry is one of the industries affected by technological innovations that emerge with industrial revolutions, since it has a dynamic nature and is the driver for the economic development of every country to a great extent. Construction industry has the power to influence other areas which is the other reason why development and innovation is important. Adaptation to the developing world with new technological development and the use of new technologies is of great importance for the construction industry. This importance has necessitated this symposium on the use of new technologies in the construction industry. Based on this point, the idea was to bring stakeholders together and discuss the future of the construction industry from today to tomorrow.

Through sessions effects of technological developments will be discussed with the goal to better understand the present and future of the architecture, engineering and construction industry. With this aim we invite papers addressing topics that may include but are not limited to the following:

- Current Approaches in Construction and Design
- Innovation in Construction and Design
- 3D Construction
- Performative, Adaptive, Interactive Designs, Artificial Intelligence, Generative Systems
- Education in Digital Era
- Digitalization in Construction and Design
- Digital Modeling – Digital Fabrication
- Building Information Modelling
- Artificial Intelligence and the Future of the Architecture and Construction Industry
- Alternate Realities (Extended Reality, Augmented Reality, Virtual Reality and Mixed Reality)
- Metaverse in the Construction Industry
- The impact of technological advances on sustainability and climate change

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PREFACE

Technological advancements have rapidly accelerated since the early 20th century, and today, they continue to progress at an unprecedented pace, driven by new-generation, advanced technologies. In our current world, adapting to this evolving landscape and embracing new technologies is paramount. The construction industry, being significantly influenced by these developments and technological innovations, led us to choose "Innovation, Technology, Digital Transformation, and The Future of the Construction Industry" as the theme for our symposium.

The Industrial Revolution, a pivotal moment in human history, has profoundly and continuously shaped technological developments over the years. This momentum in technological progress is evident across many industries, including construction, where new-generation advanced technologies are increasingly making their mark. The construction industry is particularly susceptible to these technological innovations due to its dynamic nature and its crucial role as a driving force for economic development in every country. Its capacity to influence other sectors further underscores the importance of development and innovation within it. For the construction industry, adapting to the developing world through the adoption of new technologies is of immense significance. Therefore, our symposium aimed to explore the potential changes that new technologies might bring to the construction sector and to gather all stakeholders to discuss the future of the construction industry, from today to tomorrow.

Symposium Discussions and Key Topics

Our goal was to better understand the present and future of the architecture, engineering, and construction (AEC) industry. We achieved this through engaging keynote speeches, a panel discussion at the end of the first day, and insightful sessions on the second day, all focusing on the impact of technological developments. To this end, we invited papers addressing, but not limited to, the following topics:

- Current Approaches in Construction and Design
- Innovation in Construction and Design
- 3D Construction
- Performative, Adaptive, Interactive Designs
- Artificial Intelligence
- Generative Systems
- Education in the Digital Era
- Digitalization in Construction and Design

- Digital Modeling – Digital Fabrication
- Building Information Modeling (BIM)
- Artificial Intelligence and the Future of the Architecture and Construction Industry
- Alternate Realities (Extended Reality, Augmented Reality, Virtual Reality, and Mixed Reality)
- Metaverse in the Construction Industry
- ... and more

Reflecting on the Past, Envisioning the Future

Before we look to the future, it is insightful to consider the past. Looking back the pace of technological advancement has undeniably and continuously accelerated. We are all experiencing incredibly rapid changes in our current era. These swift technological shifts not only present new opportunities but also fundamentally alter and transform our lifestyles and professional spheres.

Historically, the construction industry has not always kept pace with technological developments, sometimes struggling to adapt to the speed of change. It is fair to say that early innovations in construction largely stemmed from the introduction of new materials. Given current advancements in construction materials, it is reasonable to predict that material-driven developments will continue to play a pivotal role in shaping the future of the construction industry. Despite significant technological progress, modern construction remains largely labor-intensive and predominantly on-site. However, it is not overly ambitious to envision a future where prefabricated systems—featuring the off-site production of structural elements followed by on-site assembly—or the widespread adoption of 3D construction systems become more prevalent. Furthermore, discussing the potential effects of artificial intelligence on our profession, the prospective impacts of digitalization on design and construction, or the influence of technological advances on sustainability and climate change are crucial aspects that warrant further reflection and dialogue.

Key Takeaways from the Symposium

During the symposium, technological developments were evaluated from various perspectives. A prominent and frequently emphasized topic was how artificial intelligence (AI) will affect the architectural profession and the construction industry. Discussions highlighted the potential effects of AI and virtual transformation on architecture, design, and construction, urging us to prepare for the future accordingly. It was also stressed that the potential impacts of technological developments on sustainability and climate change, alongside new construction techniques and material research, will be instrumental in shaping the future of the construction industry. Although the construction industry has not always closely followed technological developments and has at times struggled to keep up, the symposium emphasized that material-focused developments will continue to play a significant role in its future, given the ongoing advancements in construction materials. Despite considerable technological progress, construction largely remains labor-intensive and mostly on-site. However, the increasing widespread use of prefabricated systems and 3D construction systems, where structural elements are produced off-site and then assembled on-site, was widely anticipated.

At the conclusion of the symposium, it was strongly emphasized that technological and all forms of innovation will bring significant developments to the construction industry, just as they have throughout history. As stakeholders in the sector, we must be prepared for this, and especially today's students, who will play a role in the future of the construction industry, should prepare themselves accordingly.

Looking Ahead

While forecasting the future comes with inherent challenges, it is essential that we prepare adequately through proactive anticipation.

Acknowledgements

I cannot conclude without expressing my sincere appreciation to the keynote speakers, panel members, and presenters for their invaluable contributions. Moreover, I owe special thanks to the scientific and organizing committees for their tremendous efforts.

Prof. Dr. Esin Kasapoğlu

Symposium Chair

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1ST SESSION

SESSION CHAIR: ASSOC. PROF. DR. ALTUĞ SARIYAR

In Architectural Education Personalized Learning Experiences with Artificial Intelligence

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Abstract

During the architectural education process, students are trained in technical knowledge, design processes, creative thinking, and offering solutions to diverse problems. New approach using AI based to needs of architectural students, would be obviously more effective than existing general and present architectural education. At this point, Artificial Intelligence (AI) come out as a supportive tool that provides an innovative approach to the educational process by creating functional and various methods. This study examines the potential of AI in architectural education and explores how personalized learning experiences can be made possible. Due to its complex and multidisciplinary fundamental, architectural education requires innovative methods that can provide to personal learning steps and needs. In this context, AI stands out as a powerful tool that supports student-based approaches.AI-based learning systems analyze student behaviors to offer content adept to personal learning styles. For sample, if a student needs more support in 3D modeling during the design process, AI algorithms can detect this need and suggest appropriate resources or provide guidance. AI can also offer tools such as virtual assistants, chat bots, or augmented reality applications to enhance interaction with students. These tools provide continuous feedback on students' projects, accelerating learning processes and creating a more interactive learning environment. Personalized learning experiences enabled by AI focus on students unique learning speeds, conditions, strengths, and weaknesses, offering a custom-defined approach that is expected to make architectural education more effective. AI tools included in this process can adapt in real time, providing responses under suitable conditions for students and assisting in enhancing their learning experiences. Through the data *generated in collaboration with students and AI, the analytical monitoring of the process's functioning and its contribution to learning experiences can provide insights and help create an optimized system to increase its impact. In this study, simultaneously usable chosen AIs varies for their specializations. Design Process Tools (MidJourney, DALL-E, ChatGPT), technical tools (Revit, Adobe Firefly), structural analysis and simulation tools (ANSYS, ETABS, Ladybug), educational feedback tools (Copilot for Design, Turnitin Ai Writing), presentation and visualition (Lumion and Endscape extensions), data analysis and educational content (GAN and Notion AI) used in this study In this context, AI tools that could grants to architectural education have been identified, and comparative observations have been made to support personalized learning experiences. It is recommended that proposed AI tools actively participate in learning experiences. Among the suggestions, it is highlighted that AI capable of generating new designs and solutions in real-time, addressing challenges in architectural education, and adaptable students' diverse perspectives should play an active role. The findings of this study, focusing on personalized learning experiences, underline the importance of utilizing AI to advance architectural education.*

Keywords: *Artificial Intelligence, Architectural Education, Personalized Learning, Architecture and Artificial Intelligence, Learning Experience*

1.Introduction

Architectural education is a multidisciplinary program that develops creative ideas, technical information, design progress, and problem-solving skills. Classical education generally works without personal needs and has general natives and equals for everyone. But every person's learning speed, knowledge accumulation, and learning capacity are different from anyone else, and they need personalized learning progress. At this point, artificial intelligence (AI) supported learning models, just adaptable for students needs, attract attention. It is thought that AI programs can provide enough support for personalized learning by adapting educational content to meet personal student needs, in this way increasing participation and learning outcomes (Göçen A, Aydemir F, 2020, p. 14). Unlike traditional education, architectural education includes not only the transfer of theoretical knowledge but also the instruction of design, functionality, aesthetics, and artistic values. During the architectural education that students receive, they experience discovering their own potential, revealing their creativity and innovative thinking structures. However, along this process, students with different thinking skills, learning capacities, and levels experience almost the same process. When architectural education is transferred like a traditional education system, there may be a disconnection between students and their learning processes due to personal differences. This situation can cause a loss of motivation and a decrease in learning performance. In this context, AI systems can be integrated to create personal learning experiences and support students in the architectural education process. AI has the potential to transform architectural education by improving pedagogical approaches and encouraging creativity (Montenegro N, 2024, p: 110) AI-supported education systems can provide solutions for personal needs by monitoring student performance and behavior. By identifying the areas where the student has difficulty and lacking, these systems help the student close the knowledge gap by providing additional materials or practical examples for those areas. For example, if a student has difficulty with 3D modeling during the design process, the system can automatically direct this student to the proper education materials. In this way, the student can gain a personalized education experience by creating a learning area suitable for him/her and practicing more on the subjects he/she has difficulty with. AI-supported education systems can also grant to the development of decision-making skills in students' design processes. In the creation processes of aesthetic and functional designs, which are included in the content of architectural education, AI can provide instant feedback and be specific to the student's needs. This feedback allows the student to see the mistakes and deficiencies in the design process and allows him/her to progress his/her design more deliberately. These systems, which help students in their design processes, can also support them in revealing their creative potential more efficiently. One of the advantages that can be observed in AI-integrated education systems is that students' education processes are more observable. In traditional education methods, students' learning processes are usually rated with exams and project submissions held at certain intervals. However, since these rating methods cannot cover the entire learning process of the student, it may not be possible to determine exactly which stages the student has difficulty in or at which points the student has made progress. However, in line with the questions, requests and needs of the student, AI programs can make it more observable in which parts the student has difficulty, which parts he pays more attention to and where he lacks. By courtesy of the ability of AI to analyze a large amount of data, it can be personalized and so the efficiency of education can be increased thanks to its adaptability to students with different learning potentials and variable sides (Yang S, 2024, p: 124). Roadmaps created with AI provide benefits such as technical skills, visualization, etc. while also helping the student to make personal criticism. (Mehan et al., 2024, p. 185). Another important factor in architectural education is the visualization and presentations of project and design courses. Visualizations and presentations of projects made by students within the scope of the course provide advantages in terms of strengthening project narrative and self-expression and also have an active and important position in their professional lives. Through AI-supported visualization and presentation tools, students can receive images more quickly and with more accessibility in line with their needs and desires. Software used for architectural drawing can create photo-realistic visuals and animations for students to present their designs.

Through that softwares, students can express themselves with a tool during the project process and present their ideas more clearly. In addition, through AI systems, not only course instructors but also students can realize their own deficiencies and needs. Students can continuously improve themselves by closely following their own learning processes and realizing their deficiencies and areas of success. This can help students manage their own learning processes more effectively. Integrating AI-supported systems in architectural education makes the educational process more efficient and effective thanks to its structure that can be personalized according to the individual learning needs of students. It is predicted that AI, especially adapted approaches, can significantly increase the quality of education and equal opportunities in education and lead to innovative educational reforms (Li Y et al., 2024, p. 691). This study aims to reveal the values that personalized learning experiences can add to the educational process by examining the contributions of AI-based tools to architectural education.

2.Method

This study was conducted to examine the contributions of artificial intelligence (AI)-supported tools to personalized learning experiences in architectural education. The research process includes the following steps:

Literature Review: A comprehensive literature review was conducted on the integration of AI in architectural education. This review aimed to compile existing knowledge on how AI can be integrated into educational processes and contribute to personalized learning experiences.

Selection of AI Tools: The AI tools to be used in the study were selected based on their potential contributions to architectural education. Tools such as MidJourney, DALL-E, and ChatGPT were chosen for design processes; ANSYS, ETABS, and Ladybug for technical analysis; and Lumion and Enscape for visualization and presentation. These tools were selected to respond to the diverse learning needs of students.

Case Studies: Case studies were conducted with architecture students to evaluate the effectiveness of the selected AI tools. These studies aimed to observe how students interact with AI tools and how these tools contribute to their learning processes. Students were encouraged to work on their projects using AI tools.

Data Collection and Analysis: During the case studies, qualitative and quantitative data were collected on students' interactions with AI tools and their learning experiences. This data was analyzed to understand how students develop personalized learning experiences. Student feedback and performance evaluations were used to measure the impact of AI tools.

Evaluation of Results: The findings were analyzed to evaluate the contributions of AI-supported tools to architectural education and how they affect personalized learning experiences. This evaluation was conducted to better understand the role of AI in architectural education and to make recommendations for future applications.

These methods provide a systematic approach to achieving the study's objectives and highlighting the potential of AI in architectural education.

3. Ai-Supported Tools in Architecture Education

Computer programs and algorithms that simulate some aspects of human intellect are included in the field of artificial intelligence (AI). Software and systems that mimic cognitive functions including learning, problem-solving, reasoning, and decision-making are how artificial intelligence operates. Since John McCarthy introduced the idea of artificial intelligence (AI) at the Dartmouth Conference in 1956, it has grown to have a variety of uses across several fields. AI's inception can be traced back to the early 1900s. Alan Turing proposed the Turing Test and questioned whether machines could reason in his 1950 paper "Computing Machinery and Intelligence." The purpose of this test was to ascertain whether a machine could mimic human behavior. Scientists like McCarthy, Minsky, Rochester, and Shannon established artificial intelligence as a recognized field of study in the late 1950s. Expert systems and knowledge-based systems contributed to the growth of AI research in the 1970s and 1980s. Algorithms used in these systems were capable of making decisions similar to those of human specialists in particular fields. However, because of their high processing power requirements and constrained data capacity, they had trouble achieving large-scale applications. Thanks to advancements in big data analysis and machine learning, artificial intelligence has accelerated since the 1990s. AI has started to be applied in many facets of daily life since the 2010s, when deep learning algorithms were developed. AI systems are made up of various fundamental parts:

• Machine Learning (ML): By automatically learning from enormous volumes of data ML, a subfield of artificial intelligence, helps computer systems perform better and generate precise predictions. ML algorithms find patterns and relationships in data to improve decision-making, in contrast to traditional programming, which explicitly defines rules. Reinforcement learning, supervised learning, and unsupervised learning are some of its important sub-branches.

• Deep Learning (DL): Artificial neural networks are used in deep learning, a specialized subset of machine learning, to interpret intricate patterns seen in big datasets. Deep learning models, which draw inspiration from the neural architecture of the human brain, can produce incredibly precise predictions, classifications, and data interpretations. These models are especially useful in sophisticated AI applications because they are composed of several layers, each of which is in charge of extracting varying degrees of characteristics.

• Automatic Decision Making: Large datasets can be processed by artificial intelligence systems with ML and DL capabilities to produce optimal decision-making outcomes. AI systems examine the best-case situations and recommend the best solutions by weighing a variety of factors.

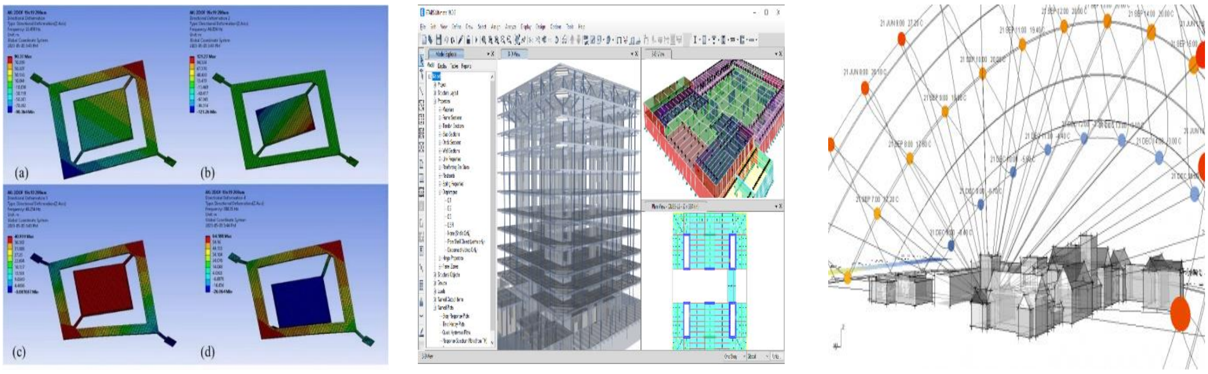
These fundamental elements serve as the foundation for future, more sophisticated systems and expand the application of AI across several industries. The phases of data gathering, processing, model building, and result generating make up AI systems. Large volumes of data are used to train an AI model, which then uses this learning process to create predictions based on fresh data. Algorithms created by simulating the neural networks of the human brain are used in artificial intelligence. AI is continuing to advance at a rapid pace. It is anticipated that AI will be incorporated into more industries in the future. Furthermore, research is being done on sophisticated neural network models that offer reasoning and decision-making capabilities more analogous to those of humans.

a b c

Figure 1: Images obtained with the prompt “I am an architecture student, draw something that will inspire me” (a Midjourney(URL-1), b- Dall-E(URL-2), c ChatGPT(URL-3))

With the integration of AI-supported tools in architecture education, students can receive additional support in many different subjects. These tools provide support in many areas, from photo-realistic image techniques to data analysis in the analysis of technical drawings, inspiration in design processes, and visualization. In addition to learning theoretical knowledge, students in architecture education also develop aesthetic and design ideas. Students constantly produce projects in t studios to develop their designs and transform abstract concepts. In this process, AI-based design tools offer students helpful ideas to explore different design approaches. Working with AI tools to strengthen and present design ideas in project courses supports more effective project creation (Bakir R, Aldassani S, 2020, p: 345). Today, tools such as MidJourney (Figure 1-a), DALL-E (Figure 1-b) and ChatGPT (Figure 1-c) provide students with visual suggestions that can inspire their projects in line with their needs and desires and contribute to the creative design process. These AI tools can help students create different perspectives and develop design ideas by offering them many different alternative design scenarios.

In architectural projects, structural statics, climatic analyses and relationships with the immediate environment are important in terms of design. Just as Building Information Modeling (BIM) has transformed the Architecture, Engineering and Construction (AEC) industry, AI can also reshape job descriptions and educational requirements in architecture (Başarır L, 2020, p:1260). AI-supported technical analysis and simulation tools such as ANSYS (Figure 2 a), ETABS (Figure 2 b) and Ladybug (Figure 2 c) can help students evaluate their projects from a technical perspective. With these tools, students can strengthen their narrative by simulating the strength of the structure, its relationship with the environment and the decisions they make on air conditioning within the design they have created.



a b c

Figure 2: AIs that can analyze data and environment (a ANSYS(URL-4), b ETABS(URL-5), c Ladybug(URL-6))

a b c d

Figure 4: Images of Visualization Programs (a Lumion (URL-7), b Enscape(URL-8), c Genera.So(URL-9), d ArchitectGPT (URL-10))

Architecture students can do visualization studies to explain their projects better, express themselves better and strengthen their presentations. Projects made and simulated in a digital environment strengthen the narrative. In the production of digital drawings, AI-supported visualization programs such as Lumion (Figure 3a), Enscape (Figure 3b), Genera.So (Figure 3c), ArchitectGPT (Figure 3d) can help students get photo-realistic images and animations in their projects. These tools contribute to the presentation of projects in a more impressive and understandable way and can improve students' presentation skills.

In architectural education, students learn theoretical courses as well as practical courses. Depending on the content of these courses, AI programs that can follow the content of the subjects and appropriate writing style are used in order to create an infrastructure for research to be conducted both academically and in terms of the sector. The integration of AI tools into architectural education helps prepare students for the contemporary architectural sector and practice (Tabrizi and Ark, 2023, p:648) , AI programs such as Copilot for Design and Turnitin AI Writing provide students with feedback on their design projects and research, and can help students improve themselves and their projects by detecting their mistakes.

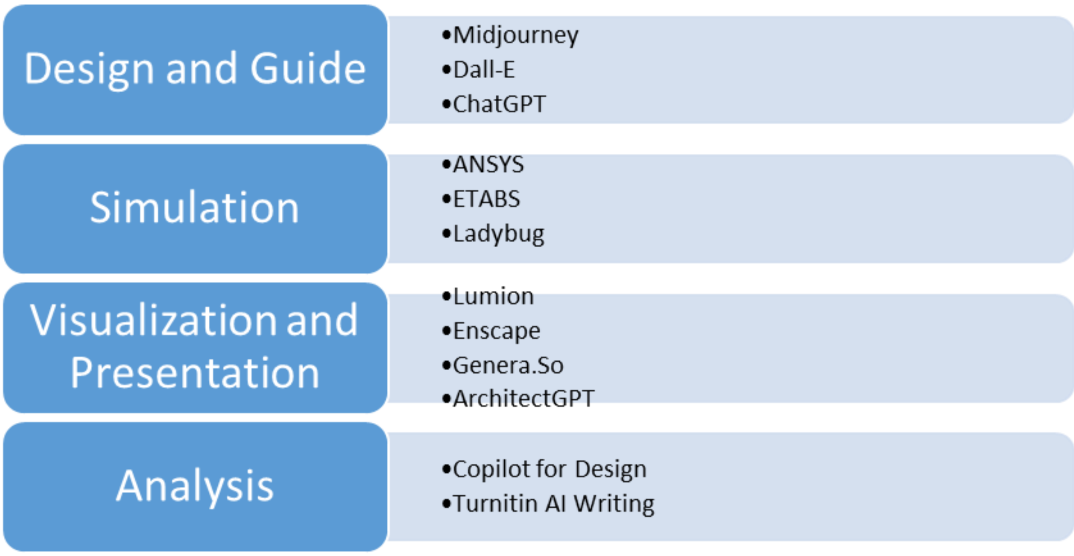


Figure 4: Some of the AI Softwares That Can Be Supported in Architecture Education

4. Conclusion

Architecture education is undergoing a transformation through AI, which offers a more customized and flexible learning environment. Students' individual skills, weaknesses, and goals are frequently not taken into account by the conventional, standardized educational system, which results in inconsistent performance and the underutilization of their entire potential. Learning becomes more effective and harmonious when AI is incorporated into the educational framework since it allows students to customize and modify their experiences. AI in architecture education offers innovative ways to track students' progress, identify areas of weakness, analyze relevant data, and provide tailored support for both academic and personal growth. In both theoretical and practical courses, students can refine their architectural skills, gain access to dynamic resources, and receive personalized feedback. By encouraging critical and creative thinking, this autonomous learning process guarantees that the final products are unique, cutting edge, and of the highest caliber. Learning can be made more efficient, engaging, and tailored to each student's individual needs with AI-based educational systems that can also adapt to their changing needs. In the upcoming years, artificial intelligence's involvement in architectural education will grow considerably as it develops and becomes more smoothly integrated into other facets of education. AI-powered learning systems' flexibility will enable them to fulfill students' varied and dynamic needs, resulting in a more effective, personalized, and efficient educational experience. AI-driven advancements are likely to have an important effect on architectural education in the future, giving students the information and capabilities they require to be successful in the rapidly shifting fields of architecture and design.

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WEB Sites

URL-1: https://chatgpt.com/

URL-2: https://www.dall-efree.com/

URL-3: https://www.midjourney.com

URL-4: https://www.researchgate.net/figure/Ansys-workbench-modal-analysis-of-the-design-a-Mode-12243-Hz-b-Mode-2-4603-Hz_fig4_372143272

URL-5: https://www.csiamerica.com/products/etabs

URL-6: https://www.food4rhino.com/en/app/ladybug-tools

URL-7: https://fga.com.tr/lumion-2024/

URL-8: https://blog.enscape3d.com/why-enscape-architectural-visualization

URL-9: https://www.genera.so/

URL-10: https://www.architectgpt.io/

3D Graphic Statics for Optimal Architectural Form and Structural Design

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Abstract

Graphic statics method has been utilized by architects for shaping innovative architectural structures since the 19th century, serving as a visual tool to illustrate the relationship between a structure's "form" and the "forces" it generates. In the 21st century, with the assistance of digital technologies, this approach has evolved from a two-dimensional analysis of thrust networks and force polygons to a three-dimensional exploration of thrust networks and force polyhedron. The aim of this study is to apply this approach to a structural form experimentally, focusing on achieving an optimal configuration to showcase the potential of the 3D graphic statics form-finding method in developing structural forms that experience pure tensile or compressive stresses without relying on complex numerical calculations. This study employs an analytical approach, beginning with a comprehensive literature review. It then proposes a design strategy to identify complex funicular spatial forms by shaping force diagrams through the aggregation of convex polyhedral cells and examining the generated forms. The outcomes demonstrate the success of using geometrical operations to create efficient structural forms that maintain perfect equilibrium with external forces and ensure that the form follows the natural force flow, reducing bending moments. Furthermore, the explanation of this design approach encourages reflection on its methods, outcomes, and how designers engage with design tools throughout the process and provides architects with insights into the advanced design tools offered by digital technology to aid architectural design, as well as how these tools differ from traditional design methods.

Keywords: *3D Graphic statics; Structural form-finding; Computational structural design; Funicular structures*

Introduction

The relationship between form generation and architecture leads to the superiority of one form over another, ultimately resulting in an optimal form. The form achieves optimality when there is an integration between the architectural and structural aspects of the design. In this state, the structure not only fulfills the structural requirements but also incorporates additional considerations. These include the alignment of the form with the load transfer path, as well as addressing economic aspects such as minimizing material usage, and considering the cost and construction time (Farshad, 1974). Form-finding can be conducted through various methods. These methods can be categorized into three groups: physical modeling, numerical methods, and graphical (geometrical) approaches. Graphical form-finding methods provide the possibility of designing structures with suitable and optimal forms and can be used under hypothetical environmental conditions (such as the size, number, and position of incoming forces and supports) for the analysis of landslides and the design of optimal form structures. In the analysis of the structure, the force diagram is made based on the geometry of the form, while in the design of the optimal structure, the force diagram is used to produce the form diagram (Barzgeri, Sadeghpour, & Alemi, 2024). Despite certain limitations in analyzing complex structural systems, graphical form-finding methods are considered powerful techniques for discovering optimal and efficient structural forms. In these methods, the equilibrium of the structure and the force distribution are controlled through the geometric structures of form and force diagrams. Furthermore, these geometric structures are interdependent. For example, each element of the force diagram is geometrically linked to a corresponding element in the form diagram. Therefore, any change in one diagram affects the geometry of the other. This feature can be effectively utilized in the process of finding efficient structural forms (Akbarzadeh, 2016).

Since the graphical representation of equilibrium using reciprocal form and force diagram provides an intuitive and insightful method of understanding a structure's behaviour through visualisation of forces that is easier to digest and more transparent than conventional, analysis-based methods of structural design (Allen & Zalewski, 2010), in this research, particular attention is given to the introduction of three-dimensional graphic statics, which falls under the graphical methods category, as an approach for generating optimized structural forms. The results of the literature analysis show an increased interest in graphic statics in scholarly publications in recent years (Figures 1, 2). By employing this approach, the study seeks to address structural design challenges and promote the efficient use of construction materials. In Section 2, the form-finding method of graphic statics and its framework is introduced. An experiment based on the three-dimensional (3D) graphic statics approach is conducted in Section 3, and the outcomes are presented and analyzed. This study is founded on the idea that employing the 3D graphic statics computational design tool, which is integrated within a standard CAD modeling system, enables designers to investigate various effective structural forms intuitively and enhance their design vocabulary during the architectural and structural design process.

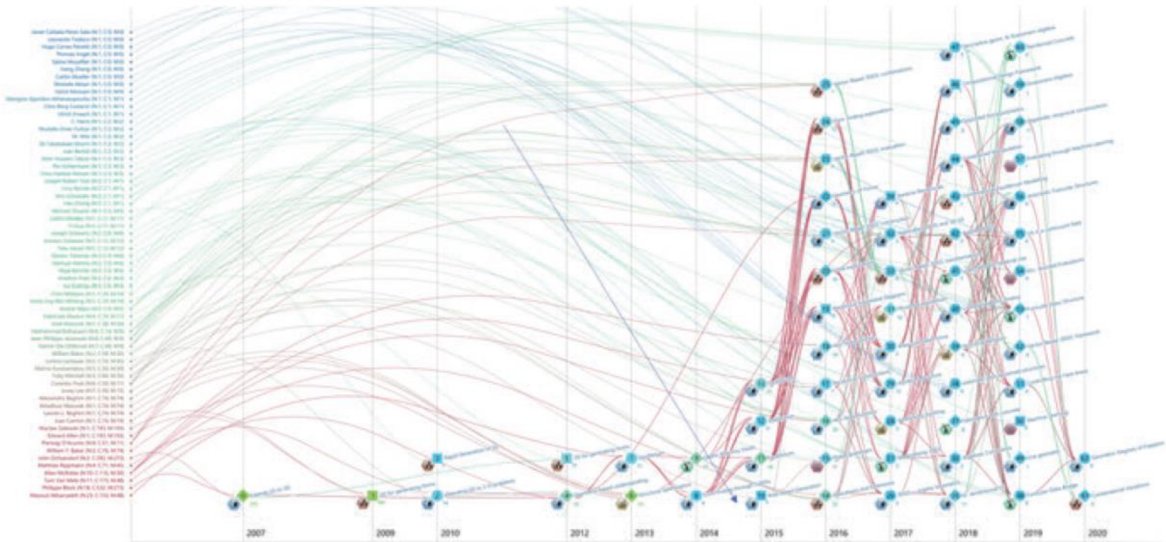


Figure 1: Literature analysis including information on number of papers (N), citation (C, M), number of authors, their impact, and connections; thematic frame; type of publication. An approach to designing architectural structures using 3D graphic statics (Milošević & Graovac, 2023).

1. Graphic Statics Form-finding Method and Framework

1.1. Graphic Statics Approach

In graphic statics, the forces acting on a structure are represented by lines or vectors, and their magnitudes and directions are accurately depicted. The graphical approach allows visualization and analysis of complex interactions of forces in a structure without complex mathematical calculations. The fundamental principle of graphic statics is based on the equilibrium of forces. By constructing reciprocal force and form diagrams, the magnitude and direction of unknown forces can be determined, and the overall equilibrium of the structure can be found (Milošević & Graovac, 2023). This characteristic makes it easier for architects without structural expertise to comprehend force equilibrium and control the geometric form of a structure. Furthermore, since the force diagram is based on geometric principles, optimizing the length of members in the force diagram also leads to an optimized distribution of internal forces and an efficient structural form (Zhi, Teng, & Akbarzadeh, 2024). Graphic statics methods are generally classified into two main categories: two-dimensional (2D) methods and three-dimensional (3D) methods. Traditional application of graphic statics involves using 2D reciprocal diagrams; however, the method was extended in 3D using the principle of the equilibrium of polyhedral forms and is known as 3D/polyhedral/spatial graphic statics. While traditional graphic statics primarily focuses on 2D structures, 3D graphic statics allows for analyzing more complex spatial structures (including trusses, frames, and arches) (Milošević & Graovac, 2023). The differences between both the two graphical representations and equilibrium are summarized in Table 1.

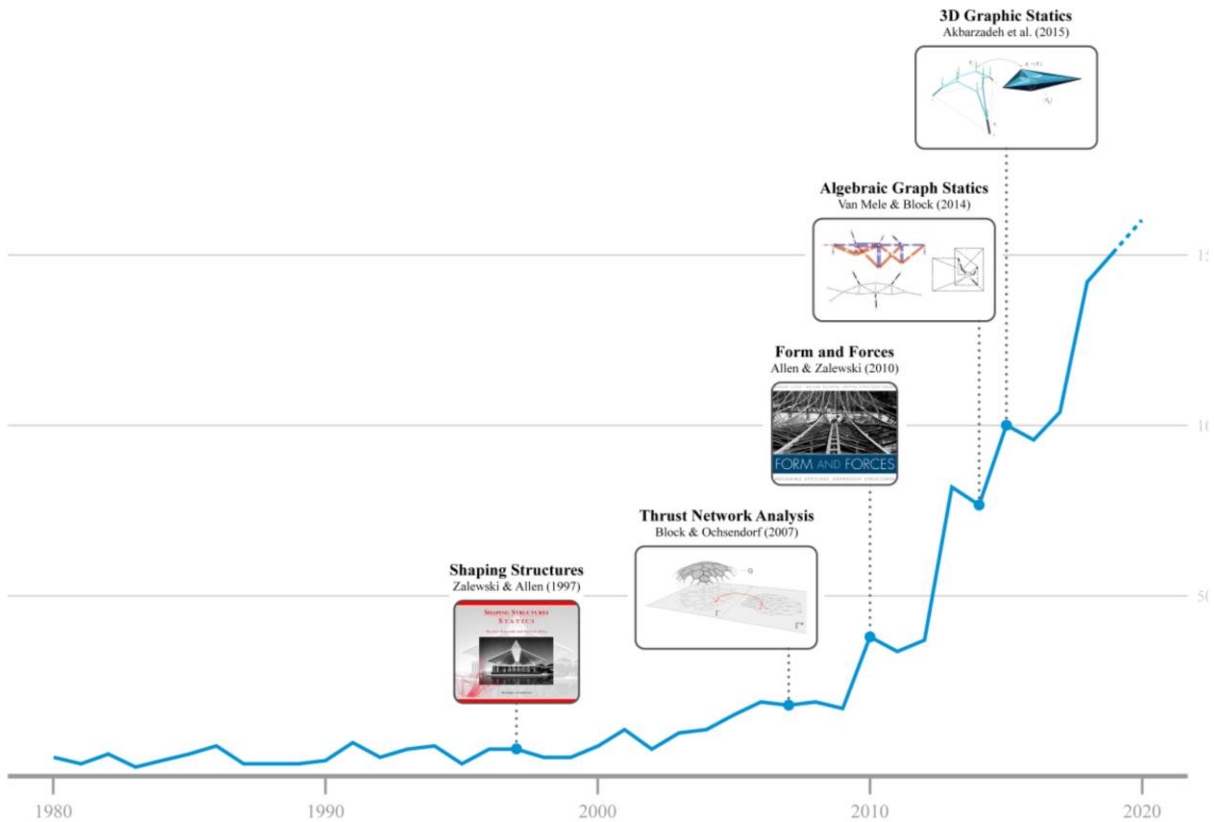


Figure 2: Recent rise in the number of graphic statics related publications and some of the notable contributions to the development of computational graphic statics based on data from

Google Scholar. Design-oriented approach to teaching structures in architecture using graphic statics (Enrique et al., 2019).

1.2. Application of Three-Dimensional Graphic Statics in Form-Finding

Graphic form-finding methods enable the design of structurally efficient and optimized forms. These methods can be utilized under assumed environmental conditions, such as the magnitude, number, and location of applied forces and supports, to analyze existing structures or to develop optimal structural forms.

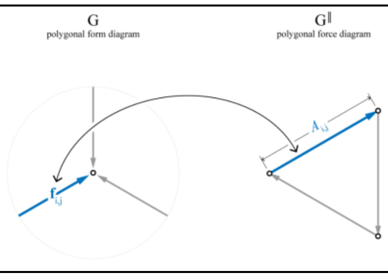
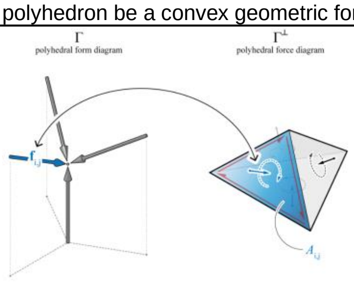
	2D Graphic Statics	3D Graphic Statics
Graphical Representations	Polygon: A force diagram in polygon, serve as visual representations of the vectorial nature of forces operating within a structural system. These diagrams are constructed through the scaled representation of individual forces as vectors, where vector magnitude directly corresponds to force intensity, and vector orientation reflects force direction. This methodology facilitates the graphical analysis of force equilibrium and the interactive relationships between forces within a defined system.	Polyhedral: This force diagram extend the concept of force representation to three-dimensional structures, utilizing polyhedral to depict force vectors. In this methodology, the edges or faces of the polyhedron are geometrically correlated with the applied forces, wherein their respective linear dimensions or surface areas are scaled to represent force magnitudes. This spatial visualization technique allows for the analysis of force equilibrium and the complex interactions of forces within three-dimensional structural frameworks.
Equilibrium Representations	Polygon Law of Equilibrium: In a two-dimensional graphical statics representation, the lines forming a force polygon must form a closed shape to indicate force equilibrium, which shows that the vector sum of all forces acting on the structure is zero, ensuring that the system remains in a state of static equilibrium.	Polyhedral Law of Equilibrium: In three-dimensional graphical statics, the vector sum of all forces on the structure are ensured to be zero, by closure of the force polyhedron, indicating a state of equilibrium. Accurate portrayal of force equilibrium necessitates that the force polyhedron be a convex geometric form.
General Principle		

Table 1: The differences between both the two graphical representations and equilibrium representations.

Note: The images in the "General Principle" row are sourced from Block Research Group (n.d.). All other content in the table is original.

In structural analysis, the force diagram is constructed based on the geometry of the form diagram. Conversely, in optimized structural design, the force diagram is used to generate the form diagram. The force diagram contains valuable information about internal and external forces, which can be creatively applied in the design of optimized structural forms. Moreover, modifications to the force diagram can introduce unique design characteristics to the final form.

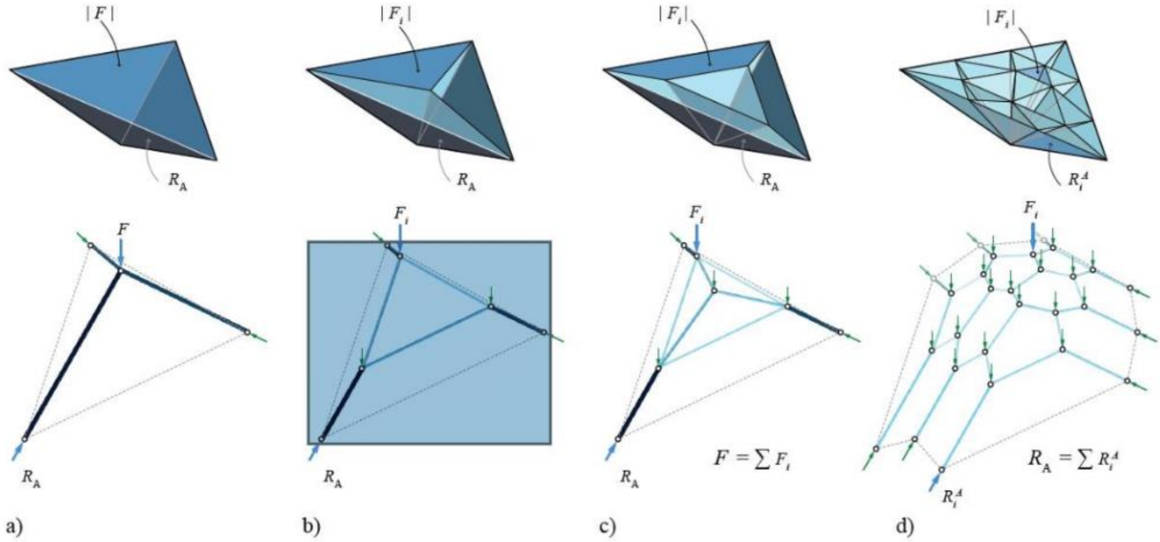


Figure 3: Changing the organization of the form from the simplest mode of push-formers to skins with flat faces using Segmentation techniques.
Reciprocal polyhedral diagram representation (Akbarzadeh, 2016)

A three-dimensional force diagram consists of both peripheral and internal polyhedra, representing global and local equilibrium of the spatial force system, respectively. In reciprocal three-dimensional form and force diagrams, the peripheral force polyhedron consists of faces that correspond to applied forces and reaction forces at the supports. The closure of this polyhedron ensures the overall equilibrium of the external forces in the system. The equilibrium of individual nodes is represented by a single polyhedron in the overall force diagram, and the balance of internal and external forces at a single node is reflected in the form diagram.

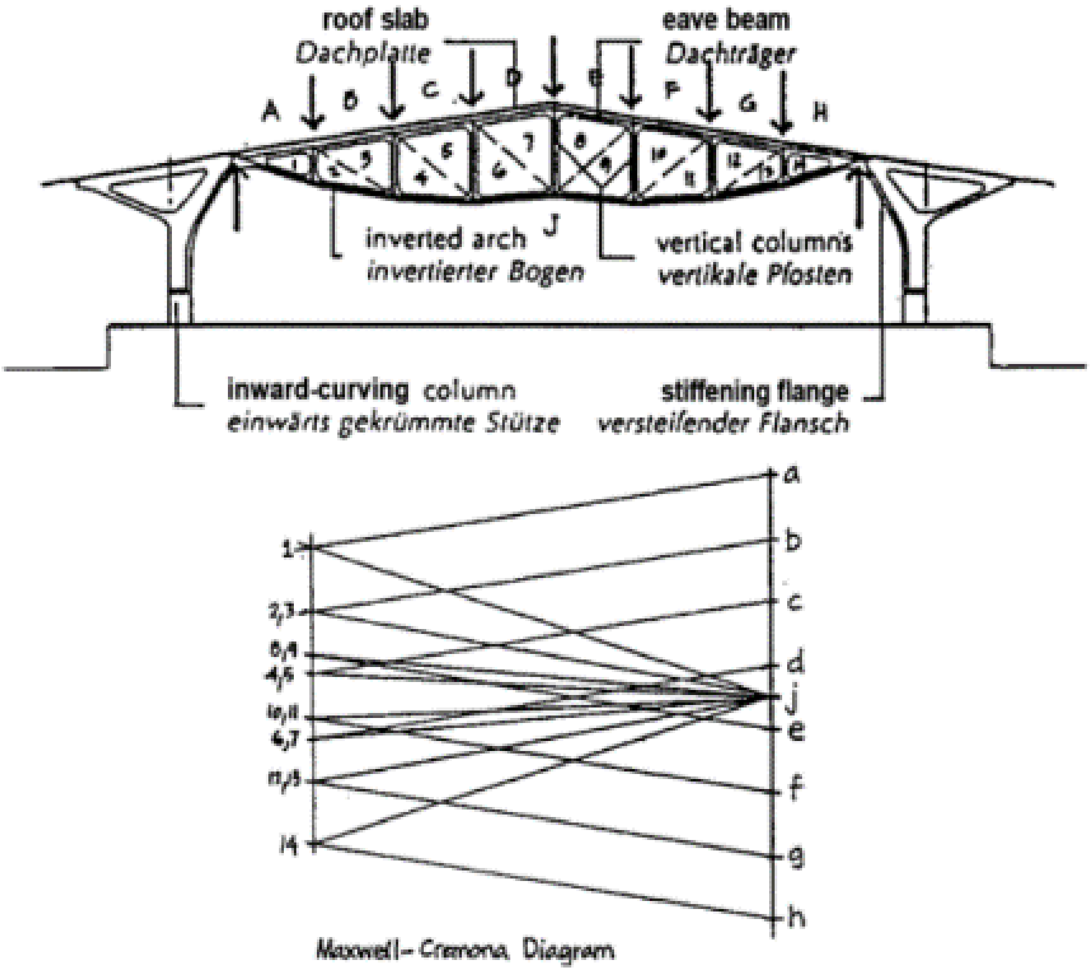


Figure 4: Robert Maillart's form and force diagram for the Chiasso City Public Warehouse Hall project.
Structural form from *Formhā-ye Sāḵtmani* (Farshad, 1974)

To extract various funicular forms, the decomposition of the global force polyhedron follows three main approaches:

- Subdivision of the face corresponding to the resultant of applied forces.

- Subdivision of the internal space of the global force polyhedron.
- Subdivision of both the internal space and the external faces of the global force polyhedron (Akbarzadeh, 2016).

This approach allows providing an approximate design with several design parameters and then modify the design through force distribution. In addition, the flatness constraint of reciprocal graphs simplifies the process of implementing such systems for architectural and construction purposes. For example, all the faces of the shell in Figure 3-d are flat. Therefore, three-dimensional graphic methods using form and force polyhedra not only provide the possibility of finding the shape of spatial structures by geometrical structures, but also simplify the construction process (Akbarzadeh, 2016).

Figure 5: Built projects designed with polyhedron-based 3D graphic statics: (a) a concrete spatial table (Akbarzadeh et al., 2021); (b) a concrete pavilion (Bolhassani et al., 2018); (c) a glass bridge (Lu, Seyedahmadian, et al., 2022); and (d) a paper bridge (Lu, Alsalem, & Akbarzadeh, 2022).

Designing 3D-printed concrete structures with scaled fabrication models (Zhi, Teng, & Akbarzadeh, 2024)

Robert Maillart is one of the engineers who, through the use of graphic statics, achieved optimal forms in remarkable examples of concrete structures. Figure 4 presents an example of his designed structure, where he utilized the reciprocal relationship between form and force diagrams to derive an optimal form (Farshad, 1974).

More recently, researchers such as Akbarzadeh, Bolhassani, Seyedahmadian, Lu, and Alsalem conducted studies and found out that while the form diagrams solved by graphic statics are primarily bar-node models with linear elements (Fig. 2a, b), research shows that they can be adapted as surface continuum models for ease of fabrication using sheet-based materials (Fig. 2c, d) (Zhi, Teng, & Akbarzadeh, 2024).

Regarding the mentioned researches, a pyramid shape, as an initial form, with different sides is investigated and evaluated in this paper using the 3D graphic statics method, in order to ensure that the forces in the structure are in equilibrium, leading to self-supporting and stable shapes while simultaneously maintaining strength.

2. Design Application and Findings

The data obtained from the force diagram of geometries in the form-finding process is regulated in graphic statics system. To generate the force diagrams of the shapes in the 3D graphic statistic approach, values of the forces emerge as a key factor. To do so, the magnitude of the loads is calculated and used to create the diagrams. Moreover, the area of the resultant face must be considered equal to the magnitude of the vertical load, while the area of the lateral face should correspond to the magnitude of the wind load. This approach generates new structural forms with pure compression or tension members by dividing the force diagram.

Unlike 2D graphic statics, 3D method is challenging to perform manually, so it was implemented in the 3D graphic statics computational tool for generating funicular structures. The development of the tool had several goals, including automation of the process of force diagrams' construction and acceleration of the design exploration process by facilitating rapid production of alternative formal solutions. The tool is implemented as a set of components within the Grasshopper environment for visual programming. It uses the advantages of real-time geometry preview, which facilitates form exploration based on simulation results (Milošević & Graovac, 2023).

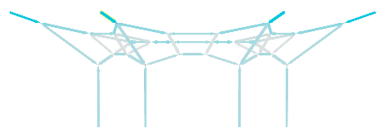
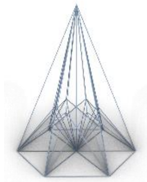
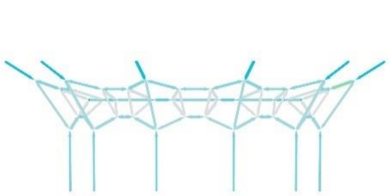
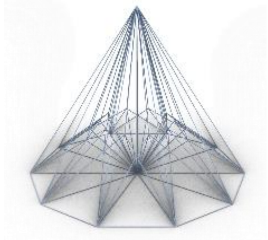
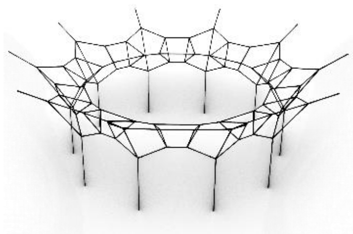
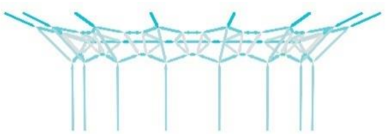
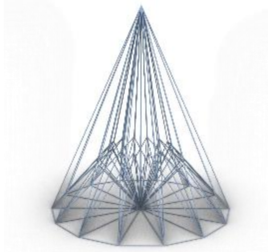
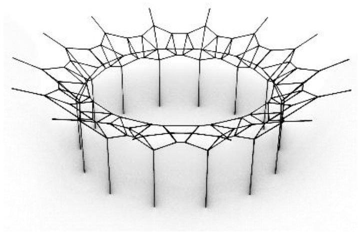
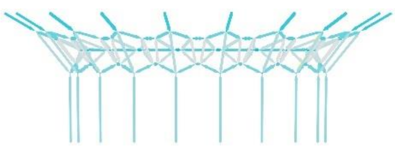
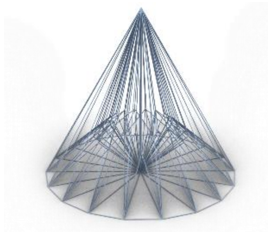
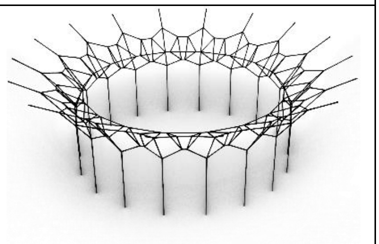
Supports	Force Intensity	Force Diagram	Form Diagram
6			
10			
14			
18			

Figure 6: Force intensity and force and form diagrams of generated structures using implemented 3D graphic statics algorithm.

For this model, pyramid shapes with edges of 6, 10, 12, and 18 sides were initiated as basic forms in the first phase. These were then calculated in the solver with maximum number of iterations of 7,000 for the component to run, an angle t “”olerance of 0.01 degrees, minimum edge length of 0.75 and Nth iteration of 100 to control and track the process. The implemented algorithm of 3D Graphic Statics enables interactive structural form-finding by manipulating both form and force diagrams in parametric settings. This form-finding algorithm comprises of two phases: preparation (phase 1) and simulation (phase 2) (Milošević & Graovac, 2023).

Phase 1, setting up the structure:

a. Place a node inside each polyhedron, to represent a key structural connection.
b. Identify how the 3D shapes are connected and link their nodes with lines. These lines demonstrate force relationships between different parts of the structure.

Phase 2, the system adjusts itself to create a stable and efficient form:

a. Rotation of the connecting lines so they align properly with the sides of the shapes.
b. Adjustment of the positions of the nodes using the arithmetic mean, so they stay balanced and connected.
c. Repeat the adjustments until all corner deviations are below tolerance (an acceptable limit of accuracy).

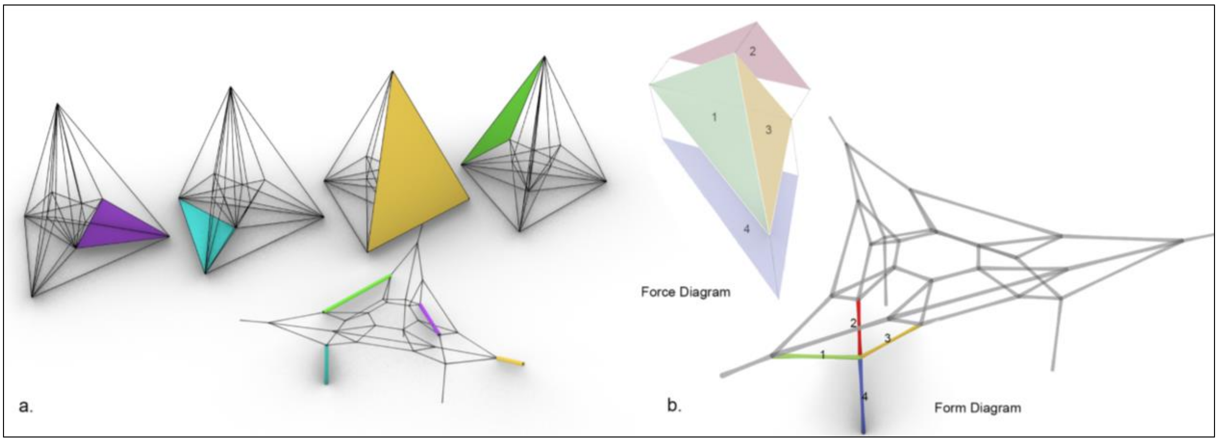


Figure 7: (a, b) Relationship between form and force diagram of four members of a 3-sided structure using 3D graphic statics method.

Figure 6 presents the outcomes of all the prepared and simulated structures, including force intensity and the force and form diagrams of each, based on 3D graphic statics calculation. To clarify the process during the phases and enhance comprehension of the relationship between force and form diagrams in the generated models, a 3-sided pyramid-based geometry is calculated as a sample, and four members of it in different directions are extracted. This illustrates the connection between the force diagram and form diagram of each member, as shown in Figure 7.

The generated forms were also evaluated through a structural analysis, providing an accurate insight into structural calculations and offering significant assistance to designers who lack sufficient knowledge of structural fundamentals. The structural analysis incorporated limits for compressive and tensile stresses, as well as an upper threshold for displacements, and identified the optimal structural configuration exhibiting minimized displacement and stress. Characteristically, these structures transfer loads via axial forces, minimizing bending moments and inducing pure tensile or compressive stresses within the members. Figure 8 shows the impact of the number of supports on the maximum tensile and compressive stresses in the generated samples. As observed, structures with 6 supports experience the highest tensile and compressive stresses compared to structures with a greater number of supports.

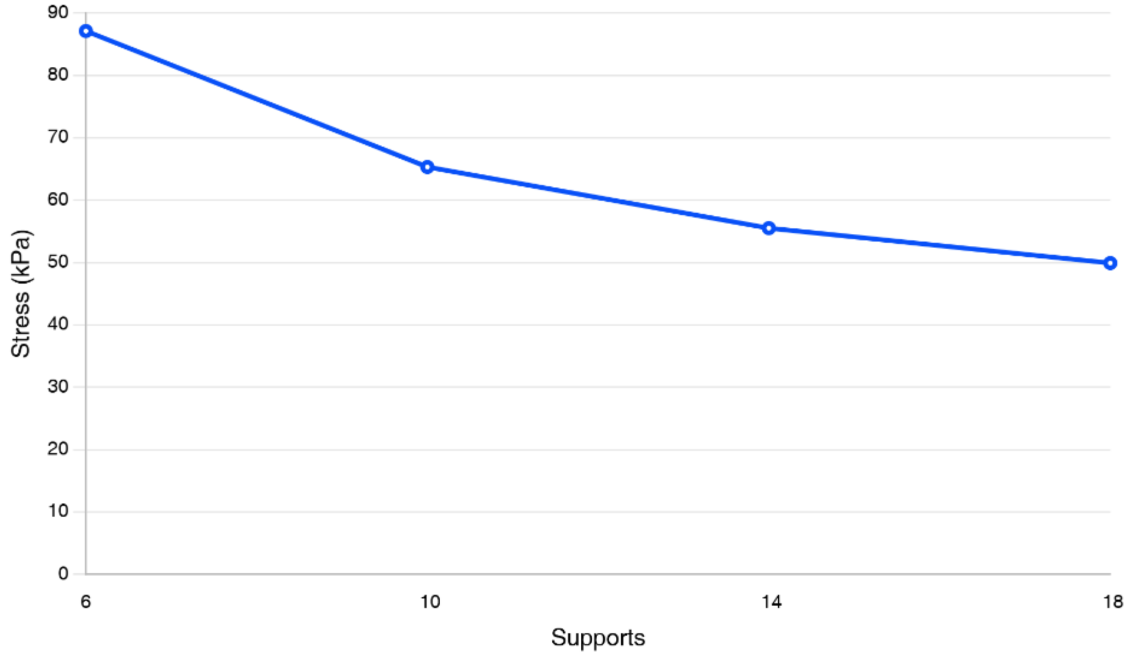


Figure 8: Influence of support count on tensile and compressive stresses**.**

More supports typically lead to lower displacement values, as seen in figure 9, because the load is shared over more points, leading to a stiffer structure. In this regard, the displacement due to bending or deflection in beams and trusses can be calculated by the following formula for simple cases: $\delta = F * L^3 / (3 * E * I)$, where:

- δ = displacement (in meters),
- F = force (in newtons),
- L = length of the span (in meters),
- E = modulus of elasticity of the material (in Pascals),
- I = moment of inertia of the cross-section (in meters^4).

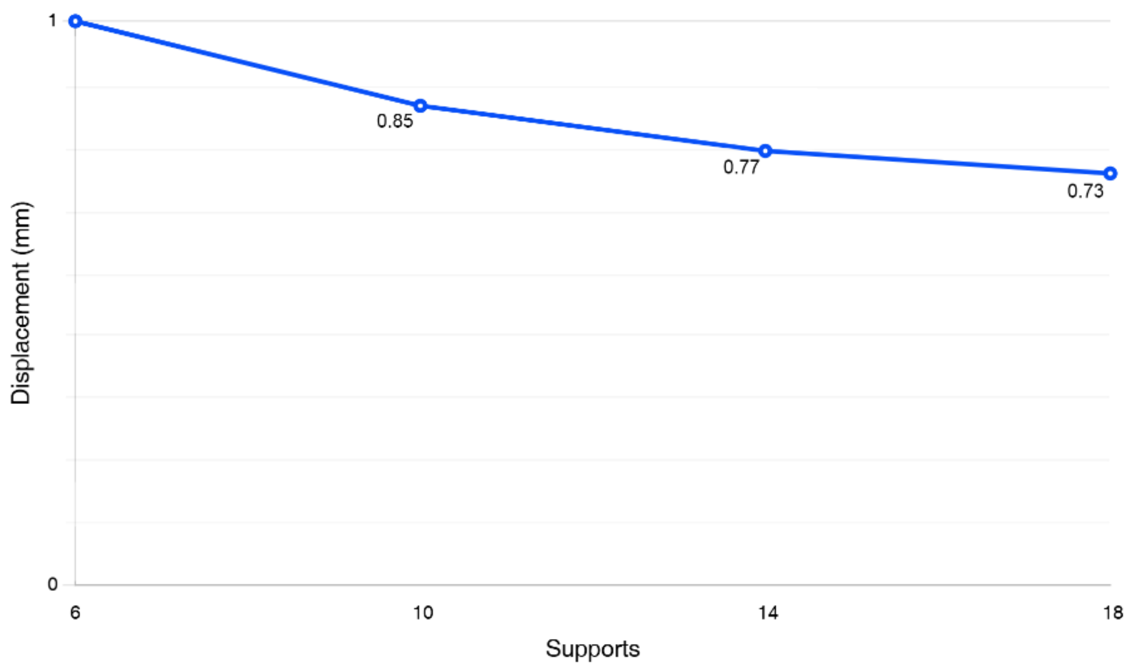


Figure 9: Influence of support count on structural displacement.

3. Conclusion

This study aimed to explore the 3D static graphics method for designing structures without complex calculations using two linked diagrams: a force diagram representing internal forces and a form diagram showing the structure's shape. Analysis of the forms derived via 3D graphic statics demonstrates that funicular structures resist loads solely through axial tensile or compressive forces. This structural behavior stems from the geometric congruence between the structural morphology and the internal force trajectories. Furthermore, by increasing the number of supports and minimizing deflection, structural displacement is reduced significantly, thereby improving lateral force resistance. This reduction in displacement correlates with a decrease in internal member forces, leading to minimized material requirements per member and contributing to overall structural optimization.

The design outcomes validate the efficacy of a geometric operation-based methodology in generating structural forms characterized by components achieving precise geometric equilibrium with applied external forces. This approach presents a sustainable design paradigm for complex spatial structures such as tensegrity and deployable structures, where form directly correlates with structural behavior. Moreover, this method is suitable for architects with limited structural knowledge, as it allows direct control over both form and forces simultaneously.

The ongoing development of graphic statics suggests promising future directions, particularly the integration of this approach with computational methodologies. Hybrid approaches, combining the visual intuition of graphical methods with the precision of computational algorithms, present a significant opportunity for advanced structural analysis and design.

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Examining the Use of Artificial Intelligence in Architectural Visualization Tools

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Abstract

Throughout human history, Architectural representation tools have helped to percept two and three dimensions of architectural design products before the construction. However, the profession of architecture and architectural representation have changed over time due to technological developments and the use of new presentation and design tools.

Today, with the widespread use of computers, firstly vectorial, then three-dimensional drawings, and finally the possibilities in visualization by artificial intelligence, have brought about a rapid development in the profession of architecture and its representation. Until very recently, architects used to make their drawings and models by hand, but today they prefer digital presentation techniques, which play an active role in shortening the design and presentation process. However, the development and rapid spread on artificial intelligence (AI), has brought about a new process. By entering the data, architects can obtain architectural visuals in a very short time.

Therefore, the main research topic of this study aims to find answers to the questions: "Can AI visualization tools replace architectural photorealistic visualization tools?", If AI provides competence for architectural design, at what stage of the design process can it take place?" and "Could architectural visualization experts be at risk of losing their jobs due to the advancement of AI applications in visualization?

In the context of this study, we considered a research study, which examine the impact levels of artificial intelligence visualization tools, and photorealistic visualization tools on the architectural project process and in which place, architects can use them effectively. We will evaluate the images produced by artificial intelligence visualization tools and photorealistic visualization tools by using a quantitative comparison method. Firstly, with the help of search on literature~~,~~ we will generate parameters to determine and compare the photorealistic visualization tools against artificial intelligence visualization tools. Our first group of *parameter refers quantitative accessibility. We will determine the economic accessibility of digital tools by obtaining data on fees and/or discounts. Second group of parameter refer utilization properties. We will find out the library and editor status of each tools and examine the user's permissions on tools. And the third group of parameter is about the process of generating the image. We will determine the features and capabilities of the tools in creating the final images.*

After all, we will use these parameters with different scales, to determine with the FIS Editor of the MATLAB tool. For making classification and rating about artificial intelligence tools, we will process each scale of parameters into a fuzzy logic system by using tables. Then, by uploading the image or model to the visualization tools, we will generate realistic images. With help of these classifications and correlations, we will examine in which areas photorealistic visualization tools and artificial intelligence visualization tools are strong, whether they can replace each other and in which areas and stages, we can use on architectural profession. We will find out the proficiency levels of each tools and evaluate the future of architectural visualization work from a professional perspective.

As a result, in addition to answer and offer suggestions for the use of artificial intelligence in architecture. This study can also form a basis for new research in the future to determine the effects of artificial intelligence visualization applications on the architectural project process and the architectural profession.

Keywords: *Artificial Intelligence; Architecture, Visualization; Tools; Architectural Digital Tools*

Introduction

The architectural profession has changed periodically throughout the history due to changes in technology and the development of presentation and design tools (Atalay v.d., 2002). According to Asar (2018), architectural design tools enable people to perceive the design before construction. At the same time, they can transform the design by affecting the process. By using the technological possibilities and design tools of their time, architects and designers developed their architectural works and presented these works to others.

When we examine the historical use of architectural design tools, we can divide them into two: traditional architectural design tools and digital architectural design tools (Yıldırım, Yavuz & İnan, 2010).

The traditional architectural design process began with graphic and verbal expressions by using paper and pencil. We use this architectural design tool with two different methods. The first one is two-dimensional drawing method by using paper and pencil that has been used since the Renaissance. By using this method, it is possible to work at all scales. It includes plans, sections and elevations by expressing certain rules (Yıldırım, Yavuz & İnan, 2010). Secondly, the three-dimensional drawing method emerged using perspective.

Another tool used in the traditional architectural design process is the model. Architects made models for using various materials according to the scale of the structure before constructions. The first recorded model occurred in the 5th century BC (Dunn, 2010). The use of a model has been preferred in the early design and project stages of architectural design from past to present.

Today, digital architectural design tools are the most preferred architectural design application and presentation tool. The reason for this is that they offer conveniences such as storability, fast solutions, impressiveness, and closeness to reality. The first digital tools used in architecture were vector-based applications for two-dimensional drawings. By using vector-based digital tools, we can make drawings such as plans, sections, views, details. They are generally preferred in all design processes and final stage of the architectural drawings.

Designers used the three-dimensional modeling tools in 1963 with Sketchpad. The CATIA program became an engineering program used in the aviation and automotive fields in 1977. Architects first started to use in the 1990s. Using these tools, we can provide visualization of details such as walls, doors, windows as well as the structure. We can obtain lively and realistic images by making furnishing layouts. We can use three-dimensional modeling tools in the early stages of design, presentation and final stage of the architectural drawings.

Over time, the use of photorealistic visualization tools has increased to support three-dimensional tools. The first example is the RenderMan program, which appeared in 1984.

Photorealistic visualization tools aim to create a realistic image by matching the camera, light, and textures with real products (Yıldırım, Yavuz & İnan, 2010). We use especially in the presentation phase of the architectural design process.

Later, BIM (Building Information Management) tools emerged, combining different contents such as analysis tools, acoustic calculation tools, cost tools with design and three-dimensional modeling tools.

The next development in the use of digital architectural tools is the inclusion of the concept of artificial intelligence in the architectural design process. Artificial intelligence (AI) is a concept that has been in our lives for 70 years. However, the use of artificial intelligence as an alternative digital application that can replace photorealistic visualization tools used in presentation and visualization of the final product (render) is still new.

The hypothesis of this study is to determine whether AI applications can replace traditional drawing techniques, digital tools, and photorealistic visualization programs in the near future.

Within the scope of this study, we try to find out the answers of these three questions: "Can AI visualization tools replace architectural photorealistic visualization tools?", If AI provides competence for architectural design, at what stage of the design process can it take place?" and "Could architectural visualization experts be at risk of losing their jobs due to the advancement of AI applications in visualization?

In order to find answers of the questions, we considered to conduct a case study that we compared the final images on data with objective and numerical values, which produced by photorealistic visualization tools and artificial intelligence tools, by using a fuzzy logic artificial intelligence system that has ability to interpret.

1. Case Study: Comparison of Photorealistic and Artificial Intelligence Visualization Tools

1.1. Method of the case study

Within the scope of the case study, we made a comparative evaluation on data with objective and numerical values. As a method, we asked produce final images of pre-made 3D models by different photorealistic visualization tools and artificial intelligence applications indetailly.

In this context, we compared photorealistic visualization tools such as V-Ray, Enscape, I umion, Unreal engine, Twinmotion and D5 Render with artificial intelligence(AI) visualization tools such as Dalle-e, mnml.ai, Midjourney, Prome AI, Evolvelab Veras, LookX, Arko AI, Renovate AI and Visoid by using concrete data, focusing on their capabilities such as having libraries, material editors, interfaces, creation of image layers, rendering speed, user-friendliness, creation of variations and furnishing placement.

	Price	Student Price	Advised system Requirements
Photorealistic Visualization Tools			
V-Ray	54,00 €	11,00 €	26.500,00 ₺
Enscape	76,90 €	11,17 €	29.000,00 ₺
Lumion	124,91€	0,00 €	27.000,00 ₺
Unreal Engine	0,00 €	0,00 €	35.000,00 ₺
Twinmotion	0,00 €	0,00 €	40.000,00 ₺
D5 Render	30,00 €	0,00 €	107.00,00 ₺
AI Visualization Tools			
Midjourney	24,00 €	(A) 8,00 €	0,00 ₺
DALL-E	20,00 €	20,00 €	0,00 ₺
Mnml AI	39,00 €	15,60 €	0,00 ₺
Prome AI	29,00 €	(A) 16,00 €	0,00 ₺
Evolvelab Veras	34,00 €	17,00 €	0,00 ₺
LookX	20,00 €	İletişim	0,00 ₺
Arko AI	31,66 €	22,50 €	0,00 ₺
Renovate AI	4,16 €	(A) 2,85 €	0,00 ₺
Visoid	23,00 €	23,00 €	0,00 ₺

Data of Numerical Accessibility about Tools

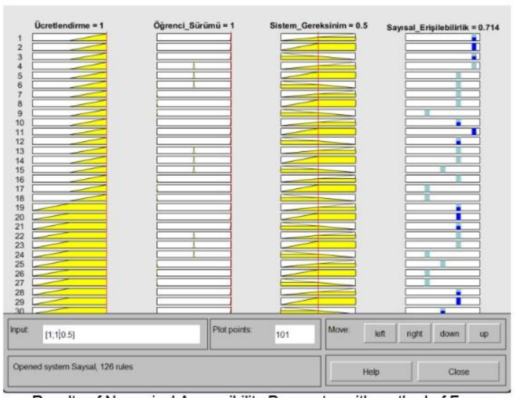
	price	price for student	Advised system requirements	Arithmetic value
Photorealistic Visualization Tools	Avarage arithmetic value 0,55			
V-Ray	(0.24)	(0.50)	(0.50)	(0.41)
Enscape	(0)	(0.50)	(0.50)	(0.33)
Lumion	(0)	(1)	(0.50)	(0.5)
Unreal Engine	(1)	(1)	(0.50)	(0.83)
Twinmotion	(1)	(1)	(0.33)	(0.77)
D5 Render	(0.51)	(1)	(0)	(0.50)
AI Visualization Tools	Avarage arithmetic value 0,61			
Midjourney	(0.61)	(0)	(1)	(0.53)
DALL-E	(0.68)	(0)	(1)	(0.56)
Mnml AI	(0.50)	(0.50)	(1)	(0.66)
Prome AI	(0.52)	(0)	(1)	(0.50)
Evolvelab Veras	(0.50)	(0.50)	(1)	(0.66)
LookX	(0.68)	(0.50)	(1)	(0.72)
Arko AI	(0.50)	(0.50)	(1)	(0.66)
Renovate AI	(0.92)	(0)	(1)	(0.64)
Visoid	(0.62)	(0)	(1)	(0.54)

(1).......................(0.75)...................(0,5)..................(0,25)....................(0)
Free/accessible Ideal Accessibilty Avarage Hard to access Expensive

Results value of Numerical Accessibility

	Arithmetic value	fuzzy logic value
Photorealistic Visualization Tools	0.55	0.535
V-Ray	0.41	0.411
Enscape	0.33	0.344
Lumion	0.50	0.562
Unreal Engine	0.83	0.714
Twinmotion	0.77	0.689
D5 Render	0.50	0.49
AI Visualization Tools	0.61	0.3915
Midjourney	0.53	0.264
DALL-E	0.56	0.278
Mnml AI	0.66	0.531
Prome AI	0.50	0.243
Evolvelab Veras	0.66	0.531
LookX	0.72	0.561
Arko AI	0.66	0.531
Renovate AI	0.64	0.319
Visoid	0.54	0.266

Fuzzy Logic Final Results Value of Numerical Accessibilty about Tools



Results of Numerical Accessibility Parameter with method of Fuzzy Logic by using FIS Editor- MATLAB tool (Unreal Engine)

Table 1: Calculation of Numerical Accessibility Parameters

	BIM Tools	Interface status	maintaining a library	Material Editor	output editor	Aritmetic Value
Photorealistic Visualization Tools	Avarage Arithmetic Value 0,78					
V-Ray	Plugin (0.5)	(0.5)	(1)	(1)	(1)	(0.80)
Enscape	Plugin (0.5)	(1)	(1)	(0.5)	(0.5)	(0.70)
Lumion	Entegre (1)	(1)	(1)	(0.5)	(0.5)	(0.80)
Unreal Engine	Entegre (1)	(0)	(1)	(1)	(1)	(0.80)
Twinmotion	Entegre (1)	(1)	(1)	(0.5)	(0.5)	(0.80)
D5 Render	Entegre (1)	(1)	(1)	(0.5)	(0.5)	(0.80)
AI Visualization Tools	Avarage Arithmetic value 0,22					
Midjourney	(0)	(1)	(0)	(0)	(0)	(0.2)
DALL-E	(0)	(1)	(0)	(0)	(0)	(0.2)
Mnml AI	(0)	(1)	(0)	(0)	(0)	(0.2)
Prome AI	(0)	(1)	(0)	(0)	(0)	(0.2)
Evolvelab Veras	Plugin (0.5)	(1)	(0)	(0)	(0)	(0.3)
LookX	(0)	(1)	(0)	(0)	(0)	(0.2)
Arko AI	Plugin (0.5)	(1)	(0)	(0)	(0)	(0.3)
Renovate AI	(0)	(1)	(0)	(0)	(0)	(0.2)
Visoid	(0)	(1)	(0)	(0)	(0)	(0.2)

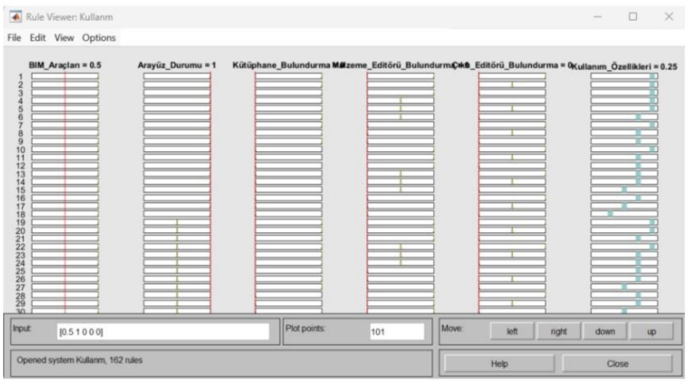
(1)................(0,75)....................(0,5)....................(0,25)......................(0)

Easy to use Available no available/useless

Results Value of Usage Features

	Aritmetic Value	Fuzzy Logic Value
Photorealistic Visualization Tools	0.78	0.95
V-Ray	0.80	1
Enscape	0.70	0.75
Lumion	0.80	1
Unreal Engine	0.80	1
Twinmotion	0.80	1
D5 Render	0.80	1
AI Visualization Tools	0.22	0.05
Midjourney	0.20	0
DALL-E	0.20	0
Mnml AI	0.20	0
Prome AI	0.20	0
Evolvelab Veras	0.30	0.25
LookX	0.20	0
Arko AI	0.30	0.25
Renovate AI	0.20	0
Visoid	0.20	0

Fuzzy Logic Final Results value of usage features about Tools



Results of usage features parameter with Method of Fuzzy Logic by Using FIS editor-MATLAB Tool

Table 2: Calculation of Usage Features Parameters

In the first phase of the case study, we produced visuals of interior and exterior spaces to be used in both photorealistic visualization tools and artificial intelligence visualization tools. For this phase, we used Sketchup program as a modeling tool for 3D visuals because it has an easier interface and is successful in fast modeling.

	Image proccesing speed	Image Channels	Image Resolution	Integrity	Revised	pre-design	variation	processing	Aritmetic Value
Photorealistic Visualization Tools	Aritmetic Value 0,558								
V-Ray	15 dk (0.85)	(1)	UHD (1)	whole (1)	(0)	(0)	(0)	at library (0.5)	useful (0.543)
Enscape	< 1 dk fast (1)	(1)	UHD (1)	whole (1)	(0)	(0)	(0)	at library (0.5)	useful (0.562)
Lumion	< 1 dk fast (1)	(1)	UHD (1)	whole (1)	(0)	(0)	(0)	at library (0.5)	useful (0.562)
Unreal Engine	< 1 dk fast (1)	(1)	UHD (1)	whole (1)	(0)	(0)	(0)	at library (0.5)	useful (0.562)
Twinmotion	< 1 dk fast (1)	(0)	UHD (1)	whole (1)	(0)	(0)	(0)	at library (0.5)	useful (0.562)
D5 Render	< 1 dk fast (1)	(1)	UHD (1)	whole (1)	(0)	(0)	(0)	at library (0.5)	useful (0.562)
AI Visualization Tools	Aritmetic Value 0,714								
~~Midjourney~~									
~~DALL-E~~									
Mnml AI	< 1 dk fast (1)	(0)	UHD (1)	whole (1)	unsuccessful (0)	(1)	(1)	(1)	talented (0.75)
Prome AI	< 1 dk fast (1)	(0)	UHD (1)	whole (1)	succesful (1)	(1)	(1)	(1)	talented (0.875)
Evolvelab Veras	< 1 dk fast (1)	(0)	UHD (1)	similar (0.5)	successful (1)	(1)	(1)	(0)	useful (0.687)
LookX	< 1 dk fast (1)	(0)	UHD (1)	similar (0.5)	successful (1)	(1)	(1)	(0)	useful (0.687)
Arko AI	< 1 dk fast (1)	(0)	HD (0.25)	similar (0.5)	successful (1)	(1)	(0)	(0)	fair (0.468)
Renovate AI	< 1 dk fast (1)	(0)	HD (0.25)	whole (1)	unsuccessful (0)	(1)	(1)	(1)	useful (0.656)
Visoid	< 1 dk fast (1)	(0)	UHD (1)	whole (1)	successful (1)	(1)	(1)	(1)	talented (0.875)

(1)..................(0,75)..................(0,5)..................(0,25)..................(0)

fast/successful/available Avarage/similar Slow/unsuccessful/unavailable

Data and Values of Image Creation Proccessing

	Aritmetic value	Fuzzy Logic Value
Photorealistic Visualization Tools	0,558	0,599
V-Ray	0.543	0.596
Enscape	0.562	0.6
Lumion	0.562	0.6
Unreal Engine	0.562	0.6
Twinmotion	0.562	0.6
D5 Render	0.562	0.6
AI Visualization Tools	0.714	0,742
~~Midjourney~~ *		
~~DALL-E~~ *		
Mnml AI	0.75	0.75
Prome AI	0.875	0.975
Evolvelab Veras	0.687	0.75
LookX	0.687	0.75
Arko AI	0.468	0.25
Renovate AI	0.656	0.75
Visoid	0.875	0.975

Fuzzy Logic Values of Image Creation Proccessing

* Midjourney and DALL-E artificial intelligence visualization tools are not included in the averages of result values due to unsuccessful results under the image creation and processing parameters.

Table 3: Calculation of Image Creation Proccessing Parameters

In the second stage, we asked photorealistic visualization tools and artificial intelligence visualization tools to create a realistic result visual using these images of interior and exterior spaces separately. We created an evaluation system for the fuzzy logic comparison system to direct questions to the tools. We preferred the MATLAB tool, which is suitable to create simple programs and contains certain strings.

In the case study, we used FIS Editor, which is one of the editors belonging to the MATLAB tool. The most important feature of the FIS Editor is that it can create an artificial intelligence fuzzy logic system consisting of three stages as input, rule and output as a result of processing the values in it (Alcı & Karatepe, 2002).

We discussed the parameters, under three headings, for comparing in the case study;

- We created a numerical accessibility parameter to obtain data on fees and/or discounts to determine the economic accessibility of vehicles.
- We organized a usage features parameter to learn about the library and editor status of the tools. We investigated to learn about the user's permissions on the tool.
- we also created an image creation processing parameter to determine the features and capabilities of the tools when we were creating the final image.

Then, we processed all these parameters by giving numerical values in the FIS Editor of the MATLAB tool. After we created the fuzzy logic system, we loaded the model image or model into the visualization tools and started the process of creating realistic result images. We will have two different types of results from the use of visuals and tools;

1. We evaluated the arithmetic results based on the scale values (3, 5 or 7 graded) found within the parameter. We determined the resulting data by calculating the evaluations.

2. We processed the responses received from the vehicles into the fuzzy logic system. We used Logical rules in the calculation of the values by the created system. We compared these values as fuzzy logic result values.

We processed all the obtained data into tables and we determined the strengths and weaknesses of all tools based on parameters. At the same time, with the help of the arithmetic average of the values taken by the tools, it was possible to discuss the digital accessibility, usage features, image creation and processing and result values of photorealistic visualization tools and artificial intelligence visualization tools.

1.2. Results of the case study

As a result of comparisons between photorealistic visualization tools and artificial intelligence visualization tools, made in terms of accessibility, usability features, and image creation and processing parameters from the case study. We obtained the following results;

- When we compared according to the digital accessibility parameter, we determined that photorealistic visualization tools are more easily accessible than artificial intelligence visualization tools. We found that the fuzzy logic values of AI visualization tools without student discounts are lower than those of photorealistic visualization tools. According to the numerical accessible parameter of student discounts, photorealistic visualization tools are more easily accessible.
- When we compared according to the usage features parameter, we determined that artificial intelligence visualization tools were unsuccessful except Evolvelab Veras and Arko AI tools that offer BIM support.
- We can say that photorealistic visualization tools give the right of choice and control to the user, unlike artificial intelligence visualization tools. The user can shape the design decisions, revision process, and furnishing the space with his/her own ideas. Based on arithmetic values, all photorealistic visualizations except “Enscape” program are very suitable in terms of usage features parameters with a score of 0.80. On the other hand, AI visualization tools show that the user can not control in terms of usage features with an average score of 0.22.
- We investigated the level of image creation, processing and editing with minimum user control with the help of image creation and processing parameter. We determined that according to the image creation and processing parameter; Visoid and Prome AI tools are the most successful tools among artificial intelligence visualization tools. We can infer photorealistic visualization tools to be functionally similar in terms of image creation by taking close/equal values to each other.
- We do not include Midjourney and DALL-E artificial intelligence visualization tools in the averages in the result values due to unsuccessful results under the image creation and processing parameters.
- When we compared photorealistic visualization tools with artificial intelligence visualization tools according to the image creation and processing parameters, we can say that artificial intelligence visualization tools are faster than photorealistic visualization tools in terms of creating, processing and preparing the image with minimum user needs. However, if the user has a sufficient computer infrastructure,

photorealistic visualization tools can produce results as fast as artificial intelligence visualization tools.

- In photorealistic visualization tools, rendering time increases as scenes get more crowded. Scene density is a common occurrence in architectural design. However, for AI visualization tolls, scene density is not a factor that slows down the speed.
- Photorealistic visualization tools can perform detailed and fast image editing operations via the editor or Photoshop because they have an output editor and image channel outputs; while we can manipulate heat and light levels in Photoshop within artificial intelligence visualization tools. However, artificial intelligence visualization tools cannot perform detailed operations such as selecting objects and increasing the reflection value by creating image layers.
- Artificial intelligence visualization tools can recognize spaces and place relatively appropriate furnishings in terms of processing furnishings. However, this process does not in detailed and does not open to editing as photorealistic visualization tools. However, since artificial intelligence visualization tools do not involve searching for objects from the library, placing them, and adjusting their angles, they shorten the visualization process time.
- Artificial intelligence visualization tools contribute to the design process by providing very fast space and material alternatives in the preliminary idea and idea project stages and facilitating the client-designer dialogue.
- We observed that the images produced by artificial intelligence visualization tools for different angles of views, at different facades or interior-exterior spaces show differences in materials, colors or design. Inconsistencies in any drawings and images related to a project are not acceptable. In the Preliminary-Final-Construction project stages, the integrity of the project and the consistency of the drawings with each other are very important for both the employer and the technical controllers.
- Although they shorten the visualization period, the fact that they do not allow the rearrangement of spaces during the design process and produce different images for the same structure in each time; causes the images produced by artificial intelligence visualization tools not to be used outside of the presentation of preliminary ideas and conceptual project stages.

0	1	2	3	4	5	6
Sketchup 3D Modelling	V-ray	Enscape	Lumion	Unreal Engine	Twinmotion	D5 Render
						
Fuzzy Logic Value	0.448	0.440	0.478	0.505	0.502	0.468
Level of Achievement	Succesful	Succesful	Succesful	Succesful	Succesful	Succesful

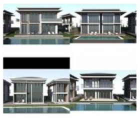
0	1	2	3	4
Sketchup 3D Modelling	Dall-e	Midjourney	mnml.ai	Prome AI
				
Fuzzy Logic Value	X	X	0.3211	0.320
Level of Achievement	Unsuccesful	Unsuccesful	Succesful	Succesful
5	6	7	8	9
Evolvelab Veras	LookX	ArkoAI	Renovate AI	Visoid
				
0.395	0.316	0.250	0.288	0.268
Succesful	Succesful	Unsuccesful	Unsuccesful	Unsuccesful

Figure 1: Creating Final Visuals with Photorealistic and AI Visualization Tools and Examining Their Success at Outdoor Modellings

0	1	2	3	4	5	6
Sketchup 3D Modelling	V-ray	Enscape	Lumion	Unreal Engine	Twinmotion	D5 Render
						
Fuzzy Logic Value	0.448	0.440	0.478	0.505	0.502	0.468
Level of Achievement	Succesful	Succesful	Succesful	Succesful	Succesful	Succesful

0	1	2	3	4
Sketchup 3D Modelling	Dall-e	Midjourney	mnml.ai	Prome AI
				
Fuzzy Logic Value	X	X	0.3211	0.320
Level of Achievement	Unsuccesful	Unsuccesful	Succesful	Succesful
5	6	7	8	9
Evolvelab Veras	LookX	ArkoAI	Renovate AI	Visoid
				
0.395	0.316	0.250	0.288	0.268
Succesful	Succesful	Unsuccesful	Succesful	Succesful

Figure 2: Creating Final Visuals with Photorealistic and AI Visualization Tools and Examining Their Success at Indoor Modellings

Conclusion

When we evaluate the results obtained from the case study, we can answer the questions "*Can AI visualization tools replace architectural photorealistic visualization tools?", If AI provides competence for architectural design, at what stage of the design process can it take* *place?" and "Could architectural visualization experts be at risk of losing their jobs due to the advancement of AI applications in visualization?"* that we asked at the beginning of the study as follows.

Considering the accessibility, usability features, and image creation and processing parameters, we found significant answers for the first research question, "*Can AI visualization tools replace architectural photorealistic visualization tools?"* by comparing visualization products. According to today's development levels. It is not possible for artificial intelligence visualization tools to replace existing photorealistic visualization tools, especially in the stages of Preliminary-Final-Construction projects. However, artificial intelligence is developing very rapidly. If artificial intelligence applications can give the user more authority in terms of control and regulation and can synthesize the data given to them and transform it into new information, it would not be wrong to predict that they can replace photorealistic images in the very near future.

When we look for an answer to the question, "*If AI provides competence for architectural design, at what stage of the design process can it take place?"*, it also shows that artificial intelligence visualization tools, with their current level of development, can be used effectively at some stages of the architectural design process. With the help of their ability to produce quick, alternative solutions and materialize instant thoughts, we can use AI at conceptual stages and facilitate dialogue with the employer.

The question of "*Could architectural visualization experts be at risk of losing their jobs due to the advancement of AI applications in visualization?"* is a debatable issue. Considering the current state of artificial intelligence visualization tools, individuals who have an architectural visualization profession should not worry about becoming unemployed due to the use of artificial intelligence. Because even if the level of development increases in the future, the power of creation in the design process will be in the hands of users in artificial intelligence applications. In the near future, with the development of artificial intelligence tools, they will be able to turn into an architectural tool that can be used throughout the entire process from the preliminary design stage to the final construction project stage.

Considering that, architectural drawing tools in different periods are used together at the same time in the past. We can say that a similar situation could be happen, for artificial intelligence applications when we remember the synergy created by the inclusion of computer drawing in the design process, there may be a possibility that different conceptual designs, new trends, new styles and new material combinations will emerge with the inclusion of artificial intelligence in the architectural design.

At the same time, we can predict that new employment opportunities and new professions may emerge in the architectural profession by using AI visualization tools. There could be architects and/or architectural AI experts who can competently use AI visualization tools. Thus, with the inclusion of artificial intelligence tools in all design stages of architectural projects, a future may be waiting for us when we can make our design decisions faster, can produce countless alternatives, and can suggest new material combinations and dialogues with the customer become easier.

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From Digital Real-Time Sketching to Interior Design: A Study on Prompt-Enhanced AI Generation

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Abstract

This study aims to evaluate the performance of the text-to-image AI platform Leonardo.ai, which utilizes a real-time canvas feature to generate images based on user-provided sketches and descriptive prompts, focusing on its application in interior design. The primary goal is to assess how effectively the model balances the representation of design styles from classical and contemporary design movements, sketch adherence, and functional requirements when creating living room designs.

The research systematically compares six distinct design styles—Art Deco, Romanesque, Renaissance from the classical period, and Modern, Futuristic, and Pop Art from the contemporary period—at three AI creativity levels (0.60, 0.75, and 0.90) to assess how real-time sketching and prompt enhancement influence design accuracy and creativity. In this study, AI creativity levels determine the extent to which the generated design deviates from the provided sketch and prompt. The closer the creativity value is to 1, the more the AI relies on its own interpretation, often diverging significantly from the original input to produce a highly creative, independent visual. Conversely, when the creativity level is below a certain threshold (e.g., 0.5 or lower), the AI adds minimal detail and closely replicates the sketch without significant enhancements.

The prompts and sketches were deliberately simplified to include only essential design elements: the space's function ("living room"), an environmental detail ("see blue sky from the windows"), and the specified design style ("a [style name] interior, living room, see blue sky from the windows"). The same simple sketch, resembling something even a child could draw, was used for all prompts to maintain consistency and evaluate how well the AI could interpret minimal visual and textual input.

In our early attempts with more detailed sketches, the AI primarily enhanced the presentation rather than demonstrating independent creative synthesis. However, this study aims to *measure the AI's ability to synthesize simple sketches with brief descriptive prompts and leverage its creativity to generate cohesive and functional living room designs.*

The AI-generated outputs are evaluated based on four criteria: “style compliance”, “prompt compliance”, “sketch compliance”, and “understanding the function of the space which is living room”. Each image is scored on a scale from 1 (poor compliance) to 5 (excellent compliance), providing a quantitative assessment of the model's performance.

The findings indicate that as creativity levels increase, the AI-generated designs become richer in stylistic details and more visually dynamic. However, this often results in deviations from the provided sketch, as the model introduces decorative elements that prioritize aesthetic complexity over spatial accuracy. Conversely, lower creativity levels produce more structured and predictable outputs that adhere closely to the sketch but lack the distinctive visual impact associated with their respective styles.

This study highlights the potential of real-time interactive tools in enhancing design processes by allowing users to guide AI-generated outputs through both visual and textual inputs. Future research could expand the scope by comparing multiple AI platforms, exploring additional room types, and incorporating user feedback on the aesthetic and emotional impact of AI-generated interiors. Such studies could further inform the development of more adaptive and user-driven AI tools for interior design.

Keywords: *Interior architecture; Interior design; Design styles; Artificial intelligence in design; Sketch-based AI generation*

Introduction

The integration of artificial intelligence (AI) into the field of interior design has significantly transformed traditional workflows, providing new tools for conceptualization, visualization, and design iteration. The intersection of AI with interior design not only streamlines operational efficiencies but also fosters innovative approaches to space utilization and environmental sustainability. One of the most significant contributions of AI to interior design is its ability to analyze vast datasets to derive insights that inform design decisions. Furthermore, AI-driven tools can automate the aesthetic evaluation of designs, enabling designers to quickly assess the visual appeal of various configurations and materials, thus expediting the design process (Zhang & Ban, 2022).

In addition to aesthetic considerations, AI plays a crucial role in optimizing functional aspects of interior design. By employing algorithms that analyze user behavior and preferences, designers can create layouts that maximize usability and comfort. For example, Liu emphasizes the importance of understanding user needs through data analysis, which can lead to more effective space planning and design solutions (Liu & Ran, 2024). This aligns with the findings of Shao, who highlights the potential of AI to generate diverse interior design styles efficiently, thereby reducing the time and effort traditionally required in the design process (Shao et al., 2024).

Today, the emergence of Artificial Intelligence (AI) tools is significantly impacting the field of interior design and architecture (Shreya & Kumar, 2024). There are many ai models and text-to-image generation is one of them. Text-to-image AI models have gained prominence for their ability to generate realistic design outputs based on descriptive prompts and user inputs. These tools enable designers to create and experiment with various styles, layouts, and atmospheres efficiently, making them valuable in both academic and professional contexts. However, the effectiveness of these models largely depends on their ability to accurately interpret user guidance, which often combines textual prompts and visual sketches.

Recent developments in AI platforms have introduced real-time canvas features, which enhance the design process by allowing users to input simple sketches alongside descriptive prompts. This dual-input system enables the user to guide the model's generation process while allowing room for AI-driven creative interpretation. However, this interactive approach raises key questions about the balance between user control and AI creativity. How well does the AI adhere to the provided sketch and prompt? At what level of creativity does the AI effectively combine both inputs to generate cohesive interior designs? And to what extent does the AI preserve the functional and stylistic requirements of the specified interior space?

This study addresses these questions by evaluating the performance of the text-to-image AI platform Leonardo.ai, focusing on its application in interior design. Leonardo.ai is a deep learning-based generative model designed to autonomously create high-quality textures and images (Jie et al., 2023). The research investigates how the AI interprets seven distinct design styles— Baroque, Art Deco, Romanesque, Renaissance from the classical period, and Modern, Futuristic, and Pop Art from the contemporary period—using a real-time sketching feature. Each style was tested at three creativity levels: 0.60 (low), 0.75 (medium), and 0.90 (high), selected based on prior observations of the model's behavior at different thresholds. The study aims to assess how effectively the model balances the representation of classical and contemporary design styles, adheres to the provided sketch, and maintains the functional elements of a living room, such as seating arrangements and spatial organization.

By systematically comparing the outputs across creativity levels, this research provides insights into the capabilities and limitations of AI-generated designs when combining user input with autonomous creativity. The findings contribute to the broader discourse on the use of AI in interior design and highlight the importance of selecting appropriate creativity levels to achieve a balance between adherence to user guidance and stylistic richness.

Literature Review

Interior design has been a constantly evolving field, with various styles emerging and influencing the way we perceive and interact with the spaces around us. This paper explores and compares how ai tools can be accurate on the history and characteristics of seven distinct interior design styles: Baroque, Art Deco, Romanesque, Renaissance, Modern, Pop Art and Futuristic styles. Classical styles such as Baroque, Romanesque, Renaissance, and Art Deco are characterized by their ornate details, grandeur, and historical significance, while contemporary styles like Modern, Futuristic, and Pop Art reflect evolving aesthetics and cultural narratives.

The historical styles of interior design from the classical period are characterized by their rich cultural heritage and aesthetic principles that have influenced contemporary practices. The classical period, particularly in ancient Greece and Rome, laid foundational elements that continue to resonate in modern interior design. The interplay of art, architecture, and decorative arts during this time established a coherent narrative that has been revisited in various forms throughout history.

The origins of interior design can be traced back to ancient civilizations, where the arrangement and decoration of spaces were not merely functional but also symbolic. Huppatz discusses how early interior design practices were often intertwined with the broader narratives of art and architecture, suggesting that the cave dwellings of prehistoric times can be seen as the first interiors, setting a precedent for later developments in Greece and Rome (Huppatz, 2012). These ancient societies emphasized harmony, proportion, and the use of space, principles that are still relevant today.

In the classical period, particularly during the Renaissance, there was a revival of classical ideals that emphasized symmetry, geometry, and the use of columns and pilasters, which are hallmarks of classical architecture. This revival influenced interior design significantly, as seen in the works of architects and designers who sought to emulate the grandeur of ancient Rome and Greece. The Baroque style, which followed, introduced more ornate and dramatic elements, often as a reaction against the restrained aesthetics of earlier periods. However, the reference provided does not adequately support the claim regarding the Baroque style's relationship to minimalism, so it has been removed (Yan, 2023).

The Renaissance period, spanning from the 14th to the 17th century, marked a significant transformation in interior design, characterized by a revival of classical antiquity and a shift towards humanism. This era introduced styles that emphasized symmetry, proportion, and classical elements, which became fundamental to Renaissance architecture and interior design. The influence of Italian Renaissance architects such as Brunelleschi and Palladio is evident in the interiors of the time, where grand spaces adorned with intricate details reflected ideals of beauty and harmony derived from ancient Roman and Greek designs (Jenkins, 2021).

The Baroque era, which lasted from the late 16th to the mid-18th century, was known for its dramatic and decorative style. Influenced by the Catholic Church’s effort to reinforce its authority, Baroque interior design featured intricate details, grand proportions, and a strong sense of movement and emotion (Lin, 2021). Architects and designers used a variety of materials, such as ornate moldings, gilded furniture, frescoes, and high ceilings, to create an atmosphere of luxury and grandeur (Lin, 2021). This extravagant and theatrical style was a striking contrast to the more balanced and rational approach of the Renaissance period that came before it (Kılıçaslan & Tezgel, 2012). The Baroque style in interior design is defined by its bold colors, luxurious fabrics, and intricate patterns. Interiors often include heavy drapery, ornate furniture, and elaborate ceiling frescoes that draw the eye upward, emphasizing height and grandeur. This focus on verticality is a key feature of Baroque design, intended to create a sense of awe and elevation for the viewer. Mirrors and reflective surfaces are also frequently used to enhance the interplay of light, further contributing to the overall atmosphere of opulence (Zhukovets, 2024).

Art Deco, a striking design style that emerged in the early 20th century—especially during the 1920s—is known for its bold, glamorous, and elegant aesthetic. It first took shape in Paris and quickly spread across the world, leaving a lasting impact on architecture and interior design. This movement reflected the desire for modernity and a break from traditional forms, influenced by the social and economic shifts that followed World War I. In interior design, Art Deco is recognized for its use of luxurious materials like woods, aluminum, stainless steel. The style is also defined by bold geometric patterns and vibrant color palettes, often thoughtfully chosen to create specific moods and atmospheres (Pradipta & Prasetyo, 2021).

In addition to its architectural significance, Art Deco has also been a source of inspiration for product design and decorative arts. The style's emphasis on craftsmanship and detail has led to its revival in various design disciplines, including furniture and decorative objects, which seek to capture the elegance and sophistication of the original movement (Andrianawati et al., 2025) This style reflects the optimism and modernity of the post-World War I era, integrating technology and industrial materials into its aesthetic (Turikova et al., 2020).

In contrast, contemporary styles such as Modern, Futuristic, and Pop Art reflect a shift towards minimalism and functionality. This evolution is underscored by the integration of various artistic movements and technological advancements that shape contemporary spaces. Modern interior design is deeply intertwined with various fields, including architecture, decorative arts, and product design. The linkage between modern architecture and design has facilitated a shift towards more innovative and expressive interior spaces, moving away from traditional aesthetics to embrace a more dynamic and user-centric approach (Wu, 2024). This transformation emphasizes the importance of openness, multifunctionality, and flexibility in design, particularly in public spaces like libraries, where user perception plays a critical role in the effectiveness of the design (Aisjah et al., 2021). The aesthetic evaluation of interior spaces also highlights the significance of visual features and cultural connotations, which reflect societal aspirations and desires for improved living environments (Zhang & Ban, 2022b). Futuristic interior design incorporates advanced technologies and innovative materials, often characterized by minimalism and a focus on sustainability. The application of digital technologies, such as Building Information Modeling (BIM), has revolutionized the design process, allowing for more efficient and creative solutions that meet the aesthetic and functional demands of modern users (Zhao et al., 2024). Furthermore, the integration of ecological principles into interior design not only enhances the aesthetic appeal but also promotes environmental sustainability, aligning with contemporary societal values (Qiu, 2018).

Pop art, emerging in the mid-20th century, has significantly influenced contemporary interior design by blurring the lines between art and everyday life. This movement democratized art, making it more accessible and relatable to the general public. The incorporation of pop art elements into interior spaces reflects a cultural shift towards embracing vibrant colors, bold patterns, and playful themes, which resonate with the diverse and multicultural nature of contemporary society (Gai et al., 2022). The demand for pop art in interior design is indicative of a broader trend that seeks to infuse personal expression and cultural identity into living spaces, making them not just functional but also visually stimulating and emotionally engaging (Gai et al., 2022). The contemporary period of interior design is marked by a rich interplay of modern, futuristic, and pop art influences. This synthesis of styles and technologies not only enhances the aesthetic quality of interior spaces but also addresses the evolving needs and preferences of users.

In conclusion, the study of interior design styles from both classical and contemporary periods reveals a dynamic interplay between historical influences and modern innovations. AI tools play a critical role in analyzing and understanding these diverse design styles, allowing for a more accurate and nuanced exploration of their histories and characteristics. By examining these seven distinct styles, this paper highlights the enduring legacy of the past while celebrating the innovations of the present, offering insights into how interior design continues to shape and reflect the cultural and technological landscapes of each era.

Methodology

This study evaluates the performance of the text-to-image AI platform Leonardo.ai, which utilizes a real-time canvas feature to generate living room designs based on user-provided sketches and prompts. The research focuses on six different interior design styles—Art Deco, Romanesque, Modern, Futuristic, Renaissance, and Pop Art—tested at three creativity levels: 0.60 (low), 0.75 (medium), and 0.90 (high). The goal was to assess how well the AI model balanced stylistic representation, sketch adherence, and functional requirements when generating living room spaces.

The structured approach combined a basic sketch with a concise descriptive prompt for each style. The prompt specified the room's function ("living room"), an environmental detail ("see blue sky from windows"), and the selected design style ("a [style name] interior"). The same sketch, showing the layout with simplified outlines for furniture and windows, was used for all styles to maintain consistency.

In this study, the sketch provided to the AI was deliberately kept simple, resembling something that even a child could draw. This approach was chosen to evaluate the model's ability to interpret minimal visual input and combine it with the descriptive prompt to create a cohesive interior design. In earlier trials (Figure 1), more detailed and professional sketches were used, which resulted in the AI behaving more like a presentation tool that refined and enhanced the designer's already well-defined sketch. In these cases, the AI's contribution to the creative process appeared limited, as it mainly followed the predefined structure and added surface-level improvements.

Figure 1: An Example of the Early Trials

By contrast, the use of a simplistic sketch in this study aims to challenge the AI's capacity for independent synthesis and creativity. The simplified sketch contained only basic outlines of furniture and window placements to guide the spatial layout while leaving room for the AI to generate stylistic details based on the specified design style and creativity level. This design choice provides insights into how well the AI can operate with minimal guidance and highlights its strengths and limitations in synthesizing a full, functional interior from basic inputs.

The AI's creativity levels determined the extent to which the generated design deviated from the provided input:

- Creativity 0.60 (Low): At this level, the AI adhered closely to the sketch and prompt, contributing minimal creative enhancements and producing an output that remained highly aligned with the original layout.
- Creativity 0.75 (Medium): This level represented a balance between sketch adherence and AI-driven creativity. The AI added stylistic elements while retaining the essential spatial organization.

- Creativity 0.90 (High): At the highest creativity level, the AI heavily relied on its own interpretation, generating visually rich outputs that often deviated from the sketch in favor of complex, decorative details.

In this study, the selection of 0.60, 0.75, and 0.90 was intentional. Through earlier testing, it was observed that AI outputs at creativity levels below 0.60 contributed little beyond replicating the sketch, resulting in static and uncreative designs. At 0.60, the AI began to integrate elements from the sketch and prompt meaningfully, creating a cohesive design. The highest available creativity level, 0.90, was chosen to observe how much freedom the AI could handle before diverging too far from the original guidance. 0.75 was selected as a midpoint to evaluate how well the model balanced user input with stylistic enrichment.

Each generated image was evaluated using the following four criteria:

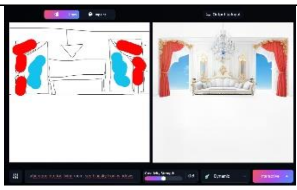
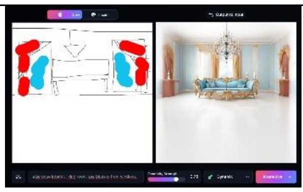
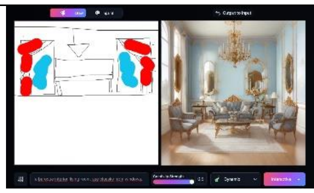
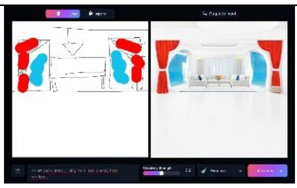
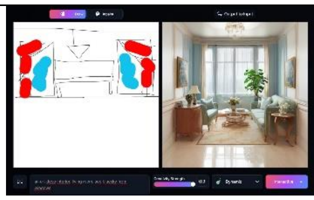
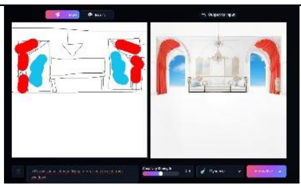
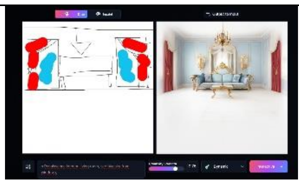
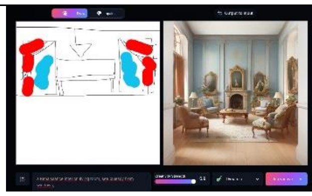
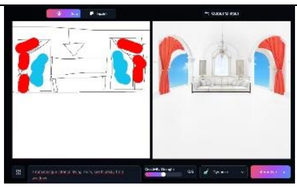
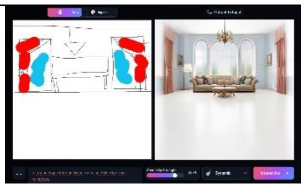
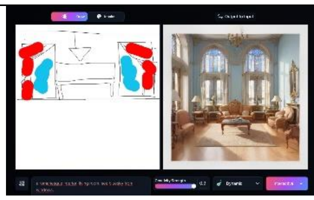
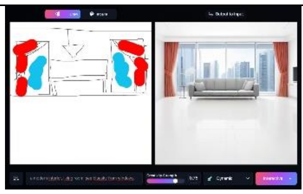
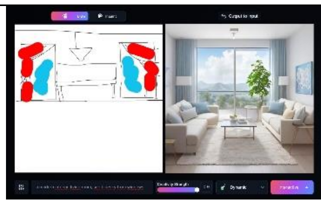
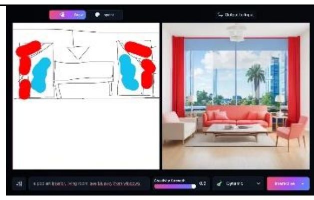
1. Style Compliance: The extent to which the design reflected the defining features of the specified style (e.g., geometric patterns for Art Deco, bold color schemes for Pop Art).
2. Prompt Compliance: How well the image fulfilled the details described in the prompt, particularly the presence of windows showing the blue sky.
3. Sketch Compliance: The degree to which the design followed the layout and furniture placement provided in the sketch.
4. Function (Living Room Recognition): Whether the space was recognizable as a living room, including appropriate seating arrangements and spatial organization.

Each criterion was scored on a scale from 1 (poor compliance) to 5 (excellent compliance). These scores were compiled into evaluation tables for each design style, highlighting the AI's performance at different creativity levels.

A comparative analysis was conducted to identify which creativity level best balanced sketch adherence with creative freedom. The analysis also examined differences in how the AI interpreted the six distinct design styles, identifying both strengths and limitations in the model's outputs across varying architectural periods and movements.

Findings

The visual outputs generated for different design styles at creativity levels 0.60, 0.75, and 0.90 are presented in Table 1.

Style	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Baroque			
Art deco			
Renaissance			
Romanesque			
Modern			
Pop art			

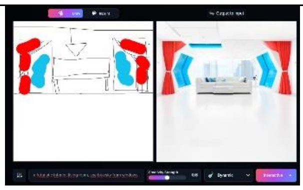
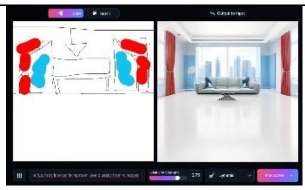
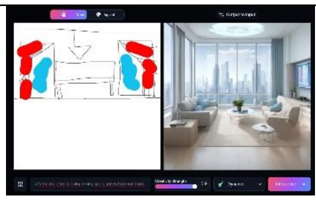
Futuristic			

Table 1: Visual Outputs of AI-Generated Interior Designs Across Different Design Styles and Creativity Levels (0.60, 0.75, 0.90)

In this context, the findings for different design styles are presented as follows.

Baroque: The design's adherence to the Baroque style improves as creativity strength increases, scoring 4 at 0.90. This indicates a rich use of Baroque-specific elements, such as elaborate detailing and luxurious ornamentation, at higher creativity. However, at 0.60 creativity, the design only scored 2, suggesting that key Baroque features, such as gilded decorations and symmetry, were not as prominent.

The prompt compliance remains relatively stable at higher levels, with a score of 4 at 0.75 and 0.90. This shows that the generated outputs largely followed the specified elements, such as windows and blue skies. However, at 0.60, the score of 3 indicates that the design may have partially overlooked or misinterpreted certain aspects of the prompt.

The best compliance with the sketch occurred at 0.75 creativity, with a score of 4. This suggests a good balance between creativity and structural fidelity. However, at 0.90 creativity, the compliance dropped significantly to 2, implying that the design diverged from the original sketch and incorporated more abstract or exaggerated elements not aligned with the initial layout.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	2	3	4
Prompt Compliance	3	4	4
Sketch Compliance	3	4	2
Function (Living Room)	5	5	5

Table 2: Evaluation of AI-Generated Baroque Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

The AI consistently understood the living room function across all creativity levels, scoring 5 at 0.60, 0.75, and 0.90. This demonstrates that the room was consistently designed with appropriate living room elements such as sofas, lighting, and spatial arrangements. The evaluation of Baroque interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 2.

Art Deco: The score improves as creativity strength increases, showing a stronger adherence to the Art Deco style at higher creativity levels (score: 4 at 0.90). However, at lower creativity (0.60), the style is less defined, suggesting that some key stylistic elements are missing or misinterpreted.

The design maintains a consistent understanding of the prompt, with a score of 4 at both 0.75 and 0.90. This shows that the AI generated spaces that generally adhere to the expected scene described in the prompt. At 0.60 creativity, however, it falls slightly short (score: 3), indicating partial omissions or inaccuracies in visualizing the described details.

The middle level of creativity (0.75) aligns best with the sketch, achieving a score of 4. However, at the highest creativity level (0.90), the alignment drops to a score of 2. This suggests that the AI introduced more abstract or unrelated elements as creativity increased, drifting away from the provided sketch.

The AI successfully interpreted the space as a living room across all levels of creativity, consistently achieving the maximum score of 5. This indicates that key elements of a living room (e.g., seating, arrangement, spatial flow) were effectively represented. The evaluation of Art deco interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 3.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	2	3	4
Prompt Compliance	3	4	4
Sketch Compliance	3	4	2
Function (Living Room)	5	5	5

Table 3: Evaluation of AI-Generated Art Deco Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

Renaissance: The lower creativity (0.60) level shows minimal Renaissance characteristics, with key details missing. However, the style improves noticeably at higher creativity levels (0.75 and 0.90), especially with classical furniture and architectural motifs.

The blue sky and windows are understood and present in all versions, though with increasing creativity, the windows are framed with more ornate, Renaissance-style decor.

The layouts somewhat follow the initial sketch at 0.60 and 0.75, with curtains, windows, and center placement respected. However, at 0.90, deviations occur due to the model's attempt to add extra detail.

All versions clearly resemble a living room with appropriate seating arrangements and functional elements, maintaining a coherent layout. The evaluation of Renaissance interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 4.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	2	3	4
Prompt Compliance	3	4	4
Sketch Compliance	3	4	2
Function (Living Room)	5	5	5

Table 4: Evaluation of AI-Generated Renaissance Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

Romanesque: The lower creativity (0.60) level shows only basic Romanesque elements, with the defining features like intricate arches and robust forms being underrepresented. However, at higher creativity levels (0.75 and 0.90), the design incorporates stronger Romanesque characteristics, such as tall arched windows, stone-like textures, and decorative pillars.

The blue sky and windows are present and understood in all versions. At the 0.75 and 0.90 levels, the framing of the windows becomes more ornate and reflective of Romanesque architecture, enhancing the connection between the interior and the view outside.

The layouts at creativity levels 0.60 and 0.75 align more closely with the original sketch, preserving the symmetry of the curtains and window positioning. However, at 0.90, the model introduces additional details that slightly alter the composition but enrich the aesthetic.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	3	4	5
Prompt Compliance	3	4	4
Sketch Compliance	3	4	2
Function (Living Room)	5	5	5

Table 5: Evaluation of AI-Generated Romanesque Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

All versions clearly convey a functional living room with appropriate seating, well-defined gathering areas, and coherent spatial organization, successfully fulfilling the purpose of the space. The evaluation of Romanesque interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 5.

Modern: The lower creativity (0.60) level displays a minimalistic approach consistent with modern design principles, but it feels somewhat underwhelming in terms of visual interest. At higher creativity levels (0.75 and 0.90), the design incorporates more refined modern characteristics, such as sleek furniture, open layouts, and large windows that enhance the sense of space.

The blue sky and windows are well-represented in all versions, with large, unobstructed openings that create a strong indoor-outdoor connection. However, at 0.90, the windows become more dynamic and frame the view in a way that accentuates the modern aesthetic.

The layouts at 0.60 and 0.75 levels follow the sketch quite closely, maintaining the placement of furniture and curtains. At 0.90, the design diverges slightly due to the addition of decorative elements and a more fluid layout that prioritizes aesthetics over strict adherence to the sketch.

All versions clearly function as a living room, with appropriate seating, a welcoming arrangement, and a cohesive organization. The living room identity is effectively maintained throughout, regardless of creativity level. The evaluation of Modern interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 6.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	3	4	5
Prompt Compliance	4	4	4
Sketch Compliance	4	4	3
Function (Living Room)	5	5	5

Table 6: Evaluation of AI-Generated Modern Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

Pop art: The lower creativity (0.60) level incorporates some bold colors and shapes typical of Pop Art but lacks the playful exaggeration and graphic details that define the style. At higher creativity levels (0.75 and 0.90), the design captures more refined Pop Art characteristics, such as vivid color blocking, whimsical decor, and statement pieces that add visual excitement.

The blue sky and windows are consistently represented across all versions, with large, unobstructed openings. At 0.90, the window frames become more integrated into the artistic composition, complementing the vibrant atmosphere of the room.

The layouts at 0.60 and 0.75 levels adhere closely to the initial sketch, retaining the placement of key furniture pieces and spatial organization. However, at 0.90, the design introduces abstract decorative elements that shift the composition, prioritizing bold visual impact over strict adherence to the sketch.

All versions effectively function as a living room, with suitable seating arrangements, lively aesthetics, and clear zoning. Despite stylistic variations, the living room's core purpose remains intact across all creativity levels. The evaluation of Pop art interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 7.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	3	4	5
Prompt Compliance	4	4	4
Sketch Compliance	4	4	3
Function (Living Room)	5	5	5

Table 7: Evaluation of AI-Generated Pop Art Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

Futuristic: The lower creativity (0.60) level presents a minimal and somewhat sterile design, consistent with futuristic aesthetics but lacking dynamic and innovative features. At higher creativity levels (0.75 and 0.90), the design incorporates more distinctive futuristic characteristics, such as curved forms, sleek metallic accents, and advanced lighting elements that enhance the sense of modernity and innovation.

The blue sky and windows are visible in all versions, emphasizing the connection between the interior and exterior. However, at 0.90, the windows become more sculptural and futuristic, contributing to the overall aesthetic rather than merely framing the view.

The layouts at 0.60 and 0.75 levels stay true to the initial sketch, maintaining the intended positioning of furniture and spatial arrangement. At 0.90, the design diverges by introducing unconventional forms and elements that prioritize style experimentation over strict adherence to the original sketch.

All versions effectively convey the function of a living room, with appropriate seating and spatial organization. Even at the highest creativity level, despite the unconventional design choices, the space remains recognizable as a living room, successfully balancing aesthetics and functionality. The evaluation of Futuristic interior designs across the three creativity levels, based on the scoring criteria, is presented in Table 8.

Evaluation Criteria	Creativity: 0.60	Creativity: 0.75	Creativity: 0.90
Style Compliance	3	4	5
Prompt Compliance	4	4	4
Sketch Compliance	4	4	3
Function (Living Room)	5	5	5

Table 8: Evaluation of AI-Generated Futuristic Interior Designs Across Creativity Levels (0.60, 0.75, 0.90) Based on Scoring Criteria

Conclusion

This study explored the performance of a text-to-image AI model using a real-time canvas feature to generate interior designs based on user-provided sketches and prompts. By examining six distinct interior design styles at three creativity levels (0.60, 0.75, and 0.90), the study aimed to evaluate how well the AI balanced style compliance, sketch adherence, and the functionality of a living room.

The results indicate that as creativity levels increased, the generated outputs displayed richer stylistic details and greater visual complexity. However, this often came at the cost of strict adherence to the initial sketch, as higher creativity levels introduced more abstract elements. Conversely, lower creativity levels produced outputs that remained closely aligned with the sketch but lacked dynamic and distinctive stylistic features. Across all creativity levels, the AI consistently recognized the functional requirements of a living room, incorporating appropriate seating and spatial organization.

This study highlights the strengths of real-time sketching tools in enabling interactive and user-guided design processes. However, it also underscores the importance of balancing creativity and precision, depending on the design objective—whether prioritizing spatial accuracy or expressive visual impact. The findings contribute to the growing discourse on the role of artificial intelligence in interior design and suggest that hybrid input methods, combining sketches and prompts, offer significant potential for future design workflows.

Future research could build on this study by comparing different AI platforms, exploring a wider range of creativity levels, and expanding the scope to include various interior spaces. Incorporating user feedback on the emotional and aesthetic impact of AI-generated designs could also provide deeper insights into how users perceive and interact with these outputs. Such research could further inform the development of more versatile and adaptive AI tools for interior design.

Limitations

One limitation of this study is the subjectivity in the evaluation process, as the scoring of the images is based on personal assessments of style, prompt adherence, and sketch compliance, which may vary between evaluators. Additionally, the study only uses the Leonardo.ai platform for generating images, meaning the results may not be generalizable to other text-to-image AI models. The focus is limited to living room designs and does not explore other types of interior spaces, such as kitchens, bedrooms, or offices.

Another limitation is that the prompts and sketches were fixed across creativity levels, which may have restricted the analysis of how flexible prompts or more complex sketches could influence the results. The AI model's interpretation of design elements may also vary due to minor wording differences in the prompts or the complexity of the sketch, affecting the consistency of the outputs. Finally, the study only tests three specific creativity levels (0.60, 0.75, and 0.90) without exploring intermediate or extreme values, which could provide more insights into how different levels of creativity impact design accuracy and style representation.

Future research could expand the scope by using multiple text-to-image AI platforms to compare their performance in generating interior designs based on sketch and prompt inputs. Exploring different room types, such as kitchens, bedrooms, and offices, could provide a broader understanding of how well AI tools adapt to various spatial functions. Additionally, testing a wider range of creativity levels, including intermediate or extreme values, could offer more nuanced insights into how creativity thresholds affect the balance between stylistic richness and sketch adherence. Studies that incorporate participant feedback on the emotional and aesthetic impact of the generated designs may also enhance the understanding of how users perceive and interact with AI-generated interior spaces.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly GO AI Writing Assistant in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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2nd SESSION

SESSION CHAIR: ASSOC. PROF. DR. GAMZE ALPTEKİN

Evaluation of the Effect of Roof Form on Wind Flow Performance of Building Surfaces

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Abstract

The rapid increase in population worldwide, coupled with the growing energy demands to meet these needs, has led to a significant consumption of energy through various technologies. The reliance on fossil fuels for energy has contributed to environmental pollution and increased carbon emissions, leading to global warming and an energy crisis. In this context, the use of renewable energy has emerged as an important solution today. Among renewable energy sources, wind energy stands out as an environmentally friendly and sustainable option. There is a strong relationship between global warming and building energy performance because buildings worldwide are major energy consumers, contributing to global warming through their energy consumption. Therefore, ensuring energy efficiency in buildings and reducing energy consumption is a critical step in mitigating environmental impacts.

Initially, wind turbines were used for energy generation in independent turbine farms, but with the advancement of turbine technologies and international decisions aimed at promoting sustainable energy use, wind turbines have gradually been integrated into buildings. As a result of technological developments in the construction sector, the production and use of integrated turbines in buildings has increased. These developments have led to the production of smaller and lighter turbines.

Today, buildings with integrated wind turbines have become a common research topic, especially in international literature, and the number of studies on this subject has increased over time. The purpose of this research is to identify the factors that affect the wind performance of buildings in the context of the relationship between buildings and wind turbines. Based on the analysis of the existing literature, the formal characteristics of building surfaces that influence wind performance will be identified to maximize the efficiency of wind energy.

The literature review reveals that wind flow analysis, wind tunnel experiments, and building form and urban fabric studies have been conducted for integrating wind turbines into buildings. The relationship between building form and wind flow can directly influence the

energy potential generated by the turbine. Furthermore, there are studies that examine the effects of roof form and building form on wind flow. The evaluation of the existing literature shows that changes in roof shape, façade form, and building shape are significant factors affecting a building's wind performance. These formal characteristics are also crucial for determining the position of turbines in integrated buildings to enhance energy efficiency.
This study will analyze the impact of roof form on wind flow, based on examples from the literature, and highlight the influence of formal characteristics that enhance wind flow on roofs. The study will provide guidance on how to increase the amount of energy generated by turbines in buildings with integrated wind turbines using renewable energy.

Keywords: *Energy Production, Wind Turbine, Sustainable Buildings, Wind Flow, Roof Form*

Introduction

The use of fossil fuels as energy sources increases environmental pollution and carbon emissions. It is believed that one of the solutions to the problems of global warming and the energy crisis is the use of renewable energy. Among renewable energy sources, wind energy is an important resource. Most buildings are major energy consumers that significantly contribute to global warming. The "2020 Global Status Report for Buildings and Construction," prepared by the United Nations Environment Programme (UNEP), revealed that in 2019, existing buildings and newly constructed buildings accounted for 35% of total energy consumption and were responsible for 38% of global carbon emissions (2020 Global Status Report for Buildings and Construction, UNEP). Energy savings through passive systems alone are not sufficient. The use of energy produced from renewable energy sources is also becoming increasingly important.

Due to factors such as increasing population, migration movements, and the demolition and reconstruction related to earthquakes, urbanization in Turkey has been rapidly increasing. Along with these activities, there has been a rise in energy consumption (Bayar, 2014: 253). The energy sources used are largely derived from fossil fuels, which exacerbate environmental pollution and carbon emissions. As a result of global warming and the energy crisis, the use of renewable energy has become one of the solutions. Among renewable energy sources, wind energy is one of the most important. There is a strong relationship between global warming and building energy performance. Most buildings around the world are significant energy consumers that contribute substantially to global warming. The general goals of this research include ensuring that our structures can generate their own energy from natural sources such as wind energy, without producing environmental waste that causes climate change, in the context of the 7th goal on affordable and clean energy, the 11th goal on sustainable cities and communities, and the 13th goal on climate action, as outlined in the United Nations' development goals. On February 19, 2022, the Ministry of Environment, Urbanization, and Climate Change introduced new provisions in the Official Gazette No. 31044 under the "Regulation on Amendments to the Energy Performance Regulation in Buildings." These provisions mandate that for Net Zero Energy Buildings (NZEB), the use of renewable energy sources to meet primary energy needs must constitute at least 10%, starting at 5% between 2023-2025. Additionally, for NZEBs larger than 2000 square meters (or 5000 square meters between 2023-2025), it is mandatory to prepare an Energy Identity Certificate along with the BEP-TR program and submit it with the building permit application. In Article 633 of the 12th Development Plan, under the subheadings 633.8, 633.9, and 633.10, there is a focus on the widespread adoption of nearly zero-energy buildings (NZEBs) and the prioritization of studies related to NZEBs in construction activities. Additionally, there is an emphasis on the development of design methods for producing energy-efficient buildings, which can be approached in a formal way. Furthermore, Article 635 of the 12th Development Plan highlights the use of products and construction techniques that focus on a sustainable built environment, contributing to the development of sustainable building design principles based on energy transformations and life cycle cost analyses. This is considered a crucial first step for the feasibility of energy-producing sustainable buildings.

With the emergence of the need for sustainable energy production, the integration of wind turbines into buildings has become a common focus of studies. These wind farms are located in rural areas, where energy is produced using turbines independent of buildings. With the advancement of turbine technologies, building-mounted and building-integrated turbines gradually began to appear in the literature. Before the idea of generating energy with wind turbines on buildings, the relationship between wind and buildings was first explored through analysis studies and wind tunnel experiments, aiming to reduce the effects of wind on tall buildings and provide optimal comfort conditions for building users. After the wind energy potential between wind and building height was discovered, the idea of increasing wind energy on buildings within the framework of sustainable energy and environmental concerns, and the possibility of storing the generated energy, emerged.

Considering the negative effects of large-scale wind turbines used in wind power plants on global climate, their environmental impact, as well as their contribution to noise and light pollution, micro wind turbines offer an alternative solution. These turbines minimize these adverse effects and provide a viable application for producing sufficient electricity in residential areas, offering a more sustainable option for energy generation in areas where people live and work.

In the research conducted on wind turbine-integrated buildings, it is observed that design criteria are crucial for optimum energy production. Based on the existing literature, it has been identified that the key design criteria for wind turbine-integrated buildings are related to environmental conditions, the structure, and the turbine itself.

This study will focus on the relationship between wind turbines and buildings, conducting a literature review and analyzing these studies. Under the topic of wind turbine-building integration, the impact of the building's roof shape on its wind performance will be investigated.

1. Methodology

Identifying suitable locations within and around a building's built environment that help efficiently harness wind energy is a crucial step in integrating wind turbines into a building. The study will focus on roof formation. In order to determine the effect of the roof surfaces' formation on wind potential, the findings from studies in the existing literature that investigate the impact of roof formation on wind potential will be analyzed. Identifying the points on the building surface where maximum utilization of wind energy can be achieved forms the first step in the process of integrating wind turbines into the building.

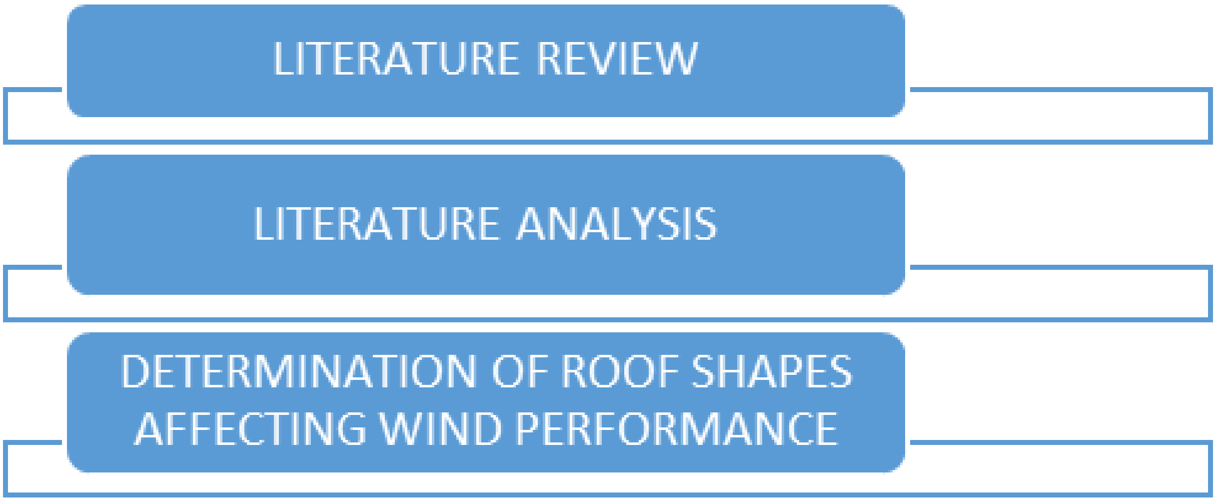


Figure 1. Flowchart of the study.

The study will be conducted based on a literature review and analysis. The Web of Science search was conducted to investigate the effects of roof shapes on wind performance in turbine integration using the keywords 'roof shape', 'turbine-integrated buildings', and 'energy performance'. After analyzing the studies accessed in the literature according to their content and the factors related to roof formation, the factors influencing roof formation in buildings affecting wind performance will be identified (Figure 1).

2. Findings

2.1. Literature Review

Firstly, the studies conducted on the topic have been examined chronologically Mertens (2002) generally classifies possible locations for incorporating a wind turbine system into a building into four groups: (a) rooftops, (b) between two buildings, (c) interior openings, and (d) integration into the building's envelope. Hasanlı and others (2017) have worked on methods related to these four groups, focusing on rooftops, interior openings, and integration into the building envelope.

Lu and Ip (2009) conducted a study to investigate the effects of building height and the "turbulence layer" above buildings. Heath et al. (2007) carried out numerical investigations on the wind field around a group of buildings. Their findings showed that the flow velocity was not significant, likely due to the complexity of wind fields in urban environments. Zhang et al. (2022) carried out a numerical study on rooftop wind turbines in an urban area by modeling 16 cubes representing 16 buildings. Due to the exclusion effect of the urban area, they found that the flow above the urban area exhibited significant acceleration and turbulence intensity increased considerably. The researchers found that the shape of the roof significantly affected the energy production of mounted wind turbines.

Ledo et al. (2011) examined the relationship between roof shapes and wind flow. By conducting wind flow simulations on houses with different roof profiles, they calculated turbulence intensity, wind speed, and wind flow models. Based on the results, they installed micro wind turbines on these roofs. The suburban topology of wind speed and turbulence intensity in a specific area is an important determinant for the optimal placement of micro wind turbines. They analyzed the working conditions of turbines for different roof profiles, such as sloped roofs, pyramid roofs, and flat roofs, using CFD. To extend the performance of wind turbines mounted on roofs, they examined wind flow around sloped, pyramidal, and flat roofs in three wind directions (0°, 45°, and 90°), concluding that power density on flat roofs is larger and more consistent. It was found that turbulence intensity is strongly dependent not only on wind direction but also on roof profiles. The wind on flat roofs has lower turbulence intensity compared to other roof profiles, and turbulence beyond the roof also decreases rapidly. In terms of wind speed, both sloped and pyramid roofs generally slow down the wind when the angle is $\alpha > 55°$ for sloped roofs and $\alpha > 67°$ for pyramid roofs. Based on turbulence intensity levels and wind speed on the roof, it was concluded that the flat roof is the most suitable shape among the three profiles considered. The power density on flat roofs is higher and more consistent compared to other roof types.

In their study, Francesco Balduzzi and others (2012) examined the relationship between roof shapes and wind flow, evaluating the energetic suitability of Darrieus vertical axis wind turbines (VAWTs). The study conducted numerical CFD analysis to characterize the flow field over building rooftops with different shapes and geometric ratios, calculating the wind speed and direction for various wind profiles. The analysis performed in a section of London observed the positive effect of the roof pitch angle on the speed increase, and it was found that the roof with an 8° pitch provided the best performance.

Abohela, Hamza, and Dudek (2013) conducted a study using Computational Fluid Dynamics (CFD) to analyze airflow over various common building roof shapes and identify key factors influencing the installation of wind turbines on roofs. The four main factors considered were roof shape, wind direction, building height, and urban configuration. Initially, the roof shapes were assessed in an isolated environment, followed by their application to urban environments with buildings of varying heights. In the first phase, the study investigated wind direction effects on roof shapes such as flat, domed, triangular, pyramid, barrel vault, and gambrel roofs (Figure 2). It was found that domed and barrel vault roofs increased wind speed, resulting in higher energy production, with the barrel vault roof achieving a 56.1% increase in power. (Figure 3) The second phase analyzed the impact of building height on wind flow, with two building heights (12 m and 24 m) modeled and compared to a 6 m case. Results showed that turbulence intensity increased with building height, and the acceleration effect of the building increased wind speed above a height of 1.35 H. In the third phase, the barrel vault roof, which yielded the best results in earlier phases, was analyzed in different urban configurations. It was found that when surrounded by buildings of the same height, the turbulence increased, but as the building height increased, the effects of roughness decreased, approaching the performance of an isolated building. Comparing the results, the optimal roof shapes for wind turbine installation were determined based on wind direction. For a wind direction of 0°, the barrel vault roof was the best choice, followed by the dome, flat, barrel, pyramid, and gabled roofs. The study concluded that the barrel vault roof was the most suitable for wind turbine installation when the wind direction was parallel to the roof profile, with the best installation position being at the center of the roof, at a height of 1.3 H. The study highlighted the effects of roof shape, wind direction, building height, and urban configuration on wind flow and turbine installation. It identified optimal positions for wind turbines on various roof shapes, emphasizing the accelerating effect of all roof shapes on wind speed. However, further research is needed to analyze wind flow on additional roof shapes and configurations with different building heights.

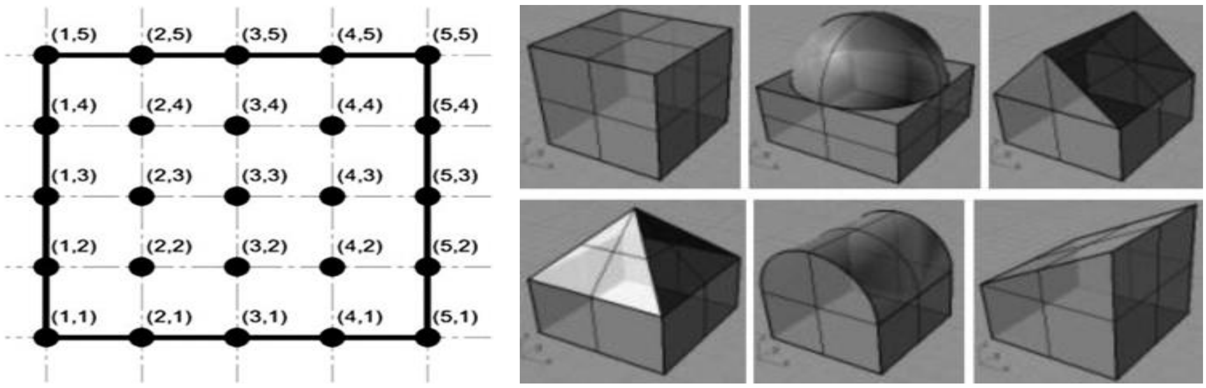


Figure 2. Used turbine locations and different roof shapes. (Abohela et al, 2013)

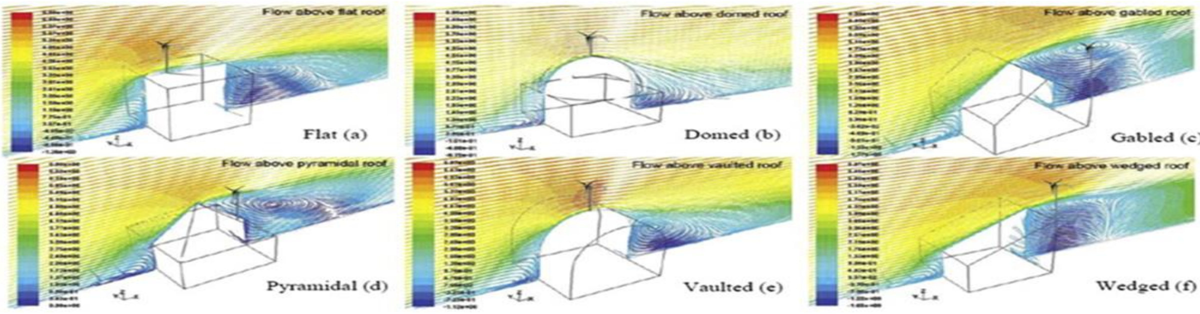


Figure 3. Different Roof Shape with turbines located in different positions (Abohela et al, 2013)

Toja Silva (2015) conducted a study on the aerodynamics of building construction, defining and analyzing the optimal building-roof shape for urban wind energy use. The study focuses on two aspects: optimization of isolated building shapes and an analysis of roof-wall transition geometry in an urban environment. In global roof shapes, turbulence intensity was reduced in all cases. Additionally, they found that a smooth transition (curved edge) between walls led to an increase in acceleration. This paper presents research on the most advantageous roof shapes for energy production (Figure 4).

Cheng and Porte-Agel (2015) found significant accelerations on the rooftops of target building groups in flat roofs. According to published research, flat roofs significantly affect the power performance of wind turbines mounted on rooftops.

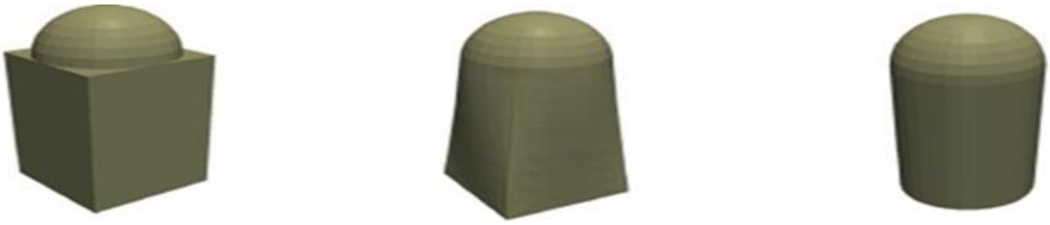


Figure 4. Evaluation of Roof-Wall Transition Geometry in Global Roof Shapes (Toja Silva, 2015)

Toja et al. (2016), based on Abohela's (2012) doctoral research, addressed the gaps and data obtained from that study in their article. This paper examines the wall-roof transition, conducts a sensitivity analysis of roof width, analyzes the effect of the building’s aspect ratio on wind flow, and investigates the impact of surrounding buildings at different heights (Figure 5).

Additionally, it was found that a smooth transition (curved edge) between the wall and roof leads to an increase in speed. The most interesting case is the cylindrical-walled, spherical roof; the acceleration, especially for HAWT (Horizontal Axis Wind Turbine), is higher than other tested cases, reaching a turbulence intensity threshold not previously achievable, allowing a HAWT to be installed at any height on the roof. Another positive aspect of the cylindrical-walled spherical roof is that its flow behavior remains consistent across all incoming wind directions. The article also notes that the roof and wall sides are suitable for wind turbine installation under the same conditions as the roof.

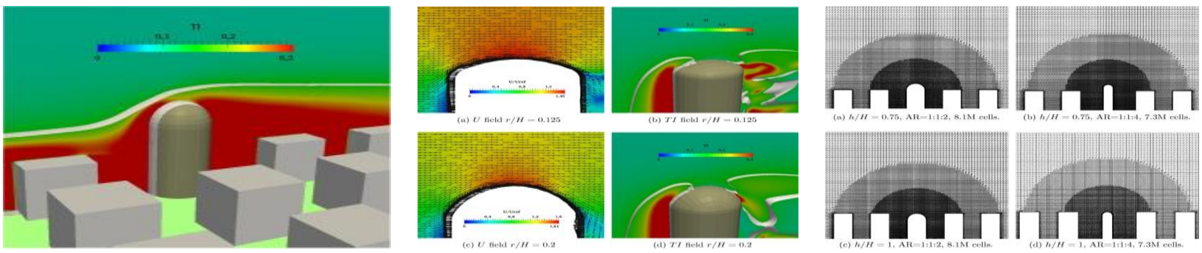


Figure 5. Analysis of Spherical Roof with Cylindrical Walls (Toja et al., 2016)

Yang et al. (2016) identified the optimal areas for turbine installation at different heights on a building in an urban area, showing that a roof with rounded corners increases wind power density and reduces turbulence. Wang et al. (2017) examined wind concentration for the installation of wind turbines on a building's canopy roof and found the best results on gable roofs with a 20-degree slope angle.

Pellegrini et al. (2021), in their research on the installation of micro wind turbines on roofs, found that flat roofs were more efficient in terms of wind flow, speed, and turbulence intensity (Ledo et al., 2021). Dar et al. (2022) conducted wind tunnel experiments to investigate the effects of roof edge shapes on the power performance of HAWTs. The study showed that placing wind turbines on roofs caused power output fluctuations on roofs with sharp edges and solid fences. However, these fluctuations were significantly reduced on roofs with rounded edges. Regardless of the turbine's position, the worst power performance was observed in the fenced roof condition (Figure 6).

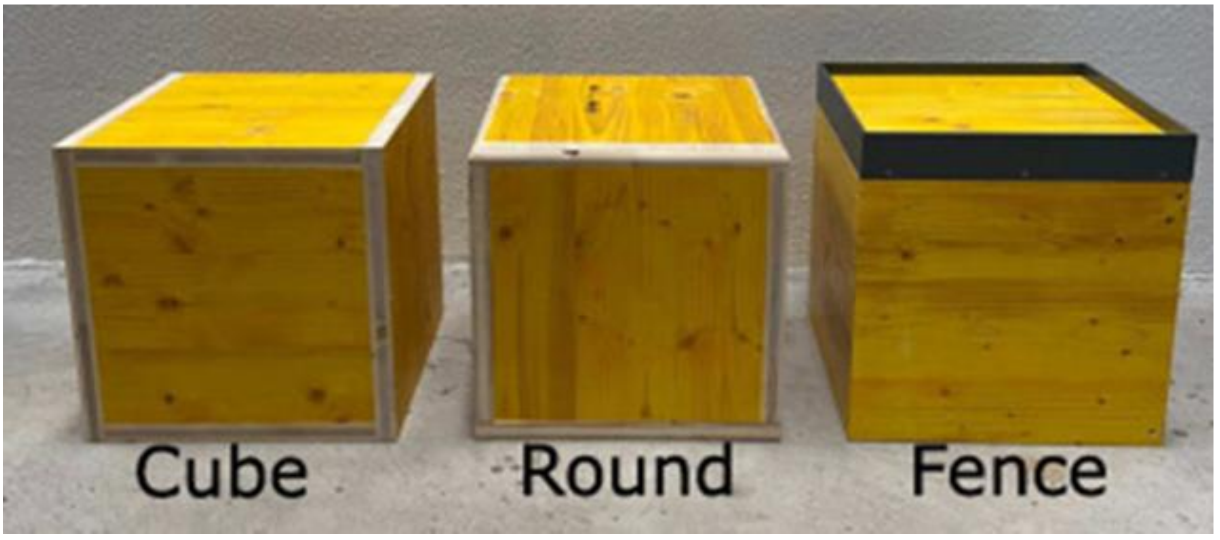


Figure 6. Evaluation of Roof Edge Shape (Dar et al, 2022)

Rızai and Paraschivoiu (2023), in their study, based on previous research, decided to place the wind turbine on the roof, specifically at the front corner and the center of the roof. To make this decision, they referred to the work of Jooss et al. (2022b), where various turbine positions, different wind directions, and changing turbine heights were examined. The results showed that wind turbines mounted on the roof performed better than other configurations (e.g., facades).

2.2. Literature Analysis

The studies assessed in the literature have been classified according to their content in Figure 7. When looking at the literature, studies related to roofs can be classified and detailed under five main headings. These headings can be listed as

- Impact of Roof Shape on Wind Flow and Energy Production
- Roof-Wall Transition Geometry and Aerodynamics
- Roof Shape Variations and Wind Flow in Urban Environments
- Wind Speed and Turbulence Intensity Analysis
- Optimal Turbine Placement for Maximum Energy Output

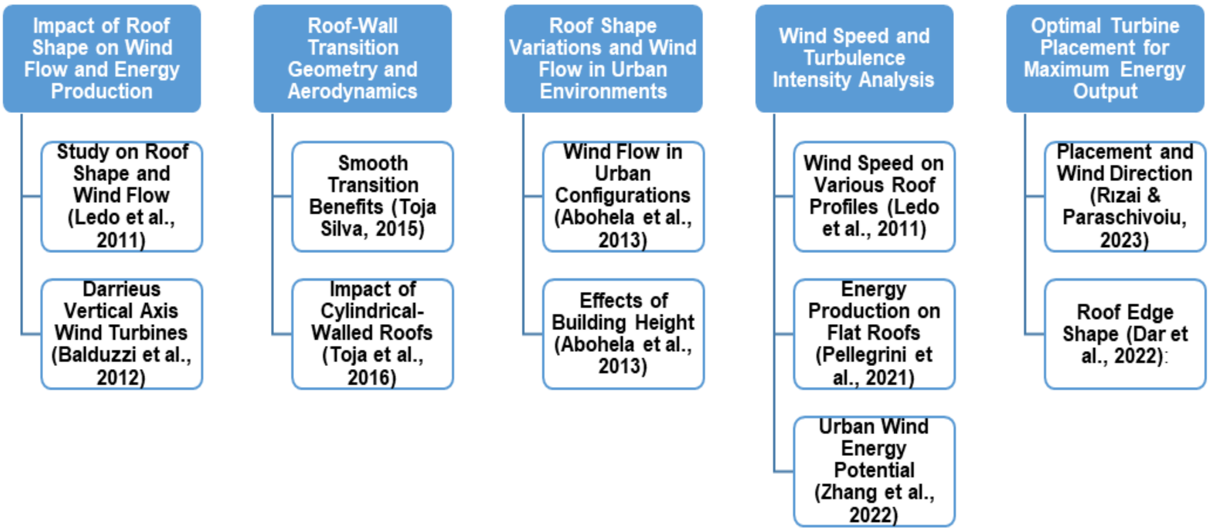


Figure 7. Classification of the Studies in Literature According to Their Content.

The study analyzes various factors influencing the integration of wind turbines into buildings, with a focus on roof shapes and their effects on wind flow. Mertens (2002) classified suitable integration locations for wind turbines into four main categories: roofs, areas between buildings, internal openings, and building envelopes. Subsequent research has focused on the most common locations for turbine installation, specifically roof spaces and areas between buildings, as outlined by Abe and Ohya (2004). High-rise buildings with rooftop installations are particularly prominent, as they capture higher wind speeds. Research by Lu and Ip (2009), Heath et al. (2007), and Zhang et al. (2022) supports the idea that roof shape and building structure play a significant role in determining wind flow characteristics and energy production potential.

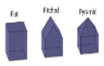
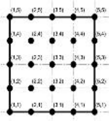
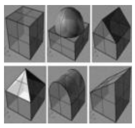
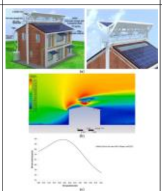
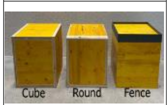
	Turbine Location	1. Roof Shape	2. Roof Surface Shape	3. Roof Joint Shape	4.Roof Height	5.Roof Slope Angle	Conclusion
Ledo vd., (2011)	Roof, Peak Point	Four-Way Sloping Roof Two-Way Sloping Roof Flat Roof	rectangle 	X	12 m 12 m 12 m	45 ° Ridge	In terms of wind speed, both sloped and pyramidal roofs generally slow down the wind when the slope angle (α) is > 55° for sloped roofs and > 67° for pyramidal roofs. To expand the performance of wind turbines, the wind flow around sloped, pyramidal, and flat roofs has been studied in three wind directions (0°, 45°, and 90°). It has been concluded that the power density on flat roofs is greater and more consistent."
abohela vd.(2013)		Flat Roof Four-Way Barrel Vault Dome Canopy gable roof	square 	sharp edged	6*1,3	X	Better results have been achieved with domed and vaulted roofs. The domed roof provides a 40.5% power increase, while the vaulted roof provides a 56.1% power increase. For both shapes, these maximum values were obtained above the center of the roofs
Toja Silva (2015)	Roof, Peak Point	dome	dome	cyclinder curved edge sharped finish 	X	X	They have found that the building with a cylindrical shape and a spherical roof, featuring soft transitions, increases the acceleration effect.
chong ve wang (2016)	roof	gable roof				X	The simulation reveals that the wind speed reaches a high velocity in the area between the roofs, which is attributed to the Venturi effect. Specifically, along the centerline of the V-shaped roof, the wind speed at measurement point '3' is 2.88 m/s (the average wind speed at the wind turbine varies between -0.06 m and 0.06 m along the centerline between the V-point). In the case of shaped roofs and gabled roofs, the wind speed is found to be 2.50 m/s, resulting in an approximately 44% increase compared to the 2 m/s incoming wind speed. Thus, the wind speed increase factor f is calculated as 1.44.
dar ve diğerleri (2022)	roof	flat roof	0	Parapet Roof (Fenced Roof Rounded Roof Sharp-edged Flat Roof 			It found that wind turbines placed on roofs with sharp edges and solid fences caused power output fluctuations, while these fluctuations were significantly reduced on roofs with rounded edges. The worst power performance occurred on roofs with fences, regardless of the turbine's position.
Farşad Rızai,Marius Paraschivoiu, (2023)	roof, corner	flat roof	0	flat			In their study, the researchers decided to place the wind turbine on the roof, specifically at the front corner and the center, based on previous research. They referred to the work of Jooss et al. (2022b), which examined various turbine positions, wind directions, and changing turbine heights. The results showed that wind turbines mounted on the roof performed better than other configurations, such as facades.

Table 1. Literature Analysis

Studies by Ledo et al. (2011) and Abohela et al. (2013) identified that certain roof shapes—particularly flat roofs—tend to provide more consistent and higher power density for wind turbines, compared to sloped or pyramid-shaped roofs. Similarly, other studies (Francesco Balduzzi et al., 2012) highlighted the positive impact of roof pitch on energy production, with roofs at specific angles (e.g., 8° in some cases) providing optimal wind conditions. Abohela et al. (2013) also used Computational Fluid Dynamics (CFD) to analyze airflow on various roof profiles, concluding that cylindrical dome roofs were the best for maximizing energy production due to their ability to increase wind speeds significantly.

Other research such as Cheng and Porte-Agel (2015) and Toja Silva (2015) further confirmed that urban environments and building shapes with curved transitions between roof and walls lead to more efficient wind energy generation. Research findings by Dar et al. (2022) and Rızai and Paraschivoiu (2023) also underlined the importance of optimizing wind turbine placement at specific points, such as the roof center or front corners, to achieve the best performance.

Ledo et al. (2011), Balduzzi et al. (2012), Abohela et al. (2013), and Toja et al. have conducted studies related to roof shape Ledo et al. (2011) simulated flow characteristics such as turbulence intensity and wind speed on the roofs of houses with different roof profiles and found that turbines mounted on flat roofs generated higher and more consistent power. Abohela et al. (2013) and Balduzzi et al. (2012) have also conducted studies related to roof pitch angle. Balduzzi (2012) found in his study that sloped roofs, with an 8° pitch, could provide significant benefits in terms of flow direction and magnitude, along with a maximized increase in wind speed. Abohela et al. (2013) conducted a CFD study on different roof shapes and building heights, showing that the vaulted roof was more efficient and could generate 56.1% more electricity.

Toja Silva (2015), Dar et al. (2022) have conducted analyses on roof joint configurations. Toja Silva (2015) conducted an analysis where the roof-wall transition geometry of a building in an urban environment was evaluated. In global roof shapes, they found that a smooth transition (curved edge) between the roof and the wall leads to an increase in acceleration. Dar et al. (2022) showed that placing wind turbines on roofs with sharp edges and ridged roofs leads to fluctuations in power output, but in roofs with rounded edges, these variations significantly decrease, resulting in better performance.

To identify the morphological factors affecting the impact of roof shapes on wind speed, the studies in existing literature have been analyzed in Table 1. The factors influencing roof formation have been determined as roof shape, roof surface shape, roof joint shape, roof height, and roof slope angle. The studies in the existing literature have been evaluated in Table 1 based on the identified factors.

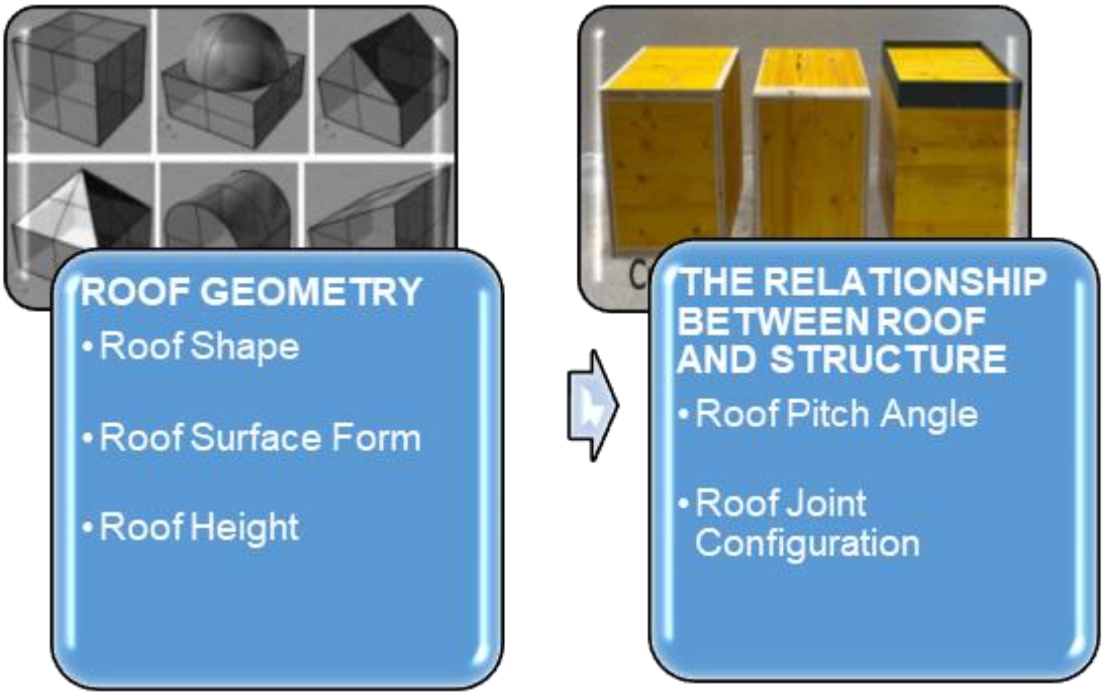


Figure 8. The Roof Related Factors that Influence Wind Potential

There are many examples in the literature where optimal energy production is achieved by altering parameters related to roof form to increase and harness wind energy. Therefore, the variables that affect the relationship between wind energy potential and roof form have been detailed based on the literature review. The roof-related factors that influence wind potential are: roof shape, roof surface form, roof pitch angle, roof joint configuration, and roof height (Figure 8).

3. Results and Conclusion

The integration of wind turbines into buildings, particularly on rooftops, is significantly influenced by the shape and design of the roof. Roof profiles like cylindrical domes, flat roofs, and specific pitched configurations are shown to optimize wind flow and energy production. The relationship between wind turbine efficiency and roof structure is complex and varies depending on factors such as wind direction, building height, and urban configuration. Flat roofs generally offer the most consistent wind speeds and power density, making them ideal for turbine placement. However, roof design is not a one-size-fits-all solution, as varying urban environments and roof types affect wind patterns differently. The optimal positioning of turbines, particularly at roof centers or front corners, also enhances energy generation. Overall, the findings emphasize the importance of architectural and environmental considerations in maximizing the effectiveness of wind turbines integrated into buildings. Further research is needed to refine optimal turbine placements and to study the interaction between building height, urban layout, and wind flow in greater detail.

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New Generation Architecture: Transcending the Conventional Boundaries of the Architect's Role

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Abstract

Architecture is a discipline that continuously evolves and expands its boundaries under the influence of technological advancements. Technology not only transforms the practice of architecture, including design, implementation and production processes, but also redefines the traditional role of the architect. The changing demands of the era, the acceleration of digitalization, and the pressures created by the sustainability crisis are among the dynamics that are reshaping the architect's role. Architecture is shaped by many parameters, including social, economic, cultural, technological, and environmental factors, in the human-centered design and construction process. Therefore, throughout history, the changing internal dynamics of different periods have led to variations in the definitions of architecture. The changing nature and boundaries of architecture have given the architect a flexible role that adjusts to different situations. This study aims to examine the effects of artificial intelligence on architectural practice, explore the role definition and skill sets of the new generation architect, and define the scientific and conceptual structure of the transformation process the architect is currently undergoing. The integration of artificial intelligence into design processes offers more creative solutions and innovative possibilities, while tools like Building Information Modeling (BIM) make design and construction processes more efficient. In this context, the role of the architect is being redefined—not only as a designer but also as a process manager, problem solver, and technology user. As the demand for conventional skills decreases and the architect's role is trimmed, opportunities arise for architects to take on new roles in emerging fields, leveraging their current knowledge, skills, and performance. With the growing digital expertise of architects and their ability to use technological tools effectively, the question of how to adapt to these changes points to the concept of next-generation architecture. The concept of next-generation architecture transcends traditional boundaries, redefining the role of the architect in a more collaborative, innovative, digital, and contemporary context. The impact of artificial intelligence-based design tools on the architect's creativity and the changes brought about by new platforms such as the metaverse in the role of the architect should be discussed within the context of the new generation of architecture. Expert intuition, the ability to make the right choices, seeing the big picture,

sustainability, inclusivity, participatory approaches, conventional knowledge, compatibility, and transdisciplinarity are important characteristics of new generation architecture. The digitalization of architectural practice and the integration of technology are radically changing the way architects work and placing new responsibilities on them. This transformation represents a significant area of inquiry into the skills and capabilities required of next-generation architects, as well as the learning and adaptation processes they must undertake. This transformation process creates an important area to discuss what skills and abilities the new generation architect should have and how they should go through a learning and adaptation process. In this context, topics such as the use of artificial intelligence in architecture, its potential effects, and future perspectives are also important parts of the study.
Keywords: *New Generation Architecture, Artificial Intelligence, Digitalization, Role of the Architect, Sustainability*

Introduction

Architecture is a discipline directly influenced by technological developments due to its constantly evolving and transforming nature. In addition to technological advancements, global issues such as the changing demands of the era, the acceleration of digitalization, and the sustainability crisis are making architectural practice more complex and multidimensional. Architectural design, which started with traditional craftsmanship and skill, became mechanized with the increased use of machines during the Industrial Revolution. With the digital age, this mechanical approach has transformed completely, giving way to algorithms, data-driven design, and computational models. Today, innovative technologies such as artificial intelligence (AI), digital fabrication, and building information modeling (BIM) are radically changing architects' design, implementation, and production processes, while also redefining the traditional role of the architect. This transformation is turning architectural practice into a dynamic process intertwined with social, environmental, and cultural factors, moving beyond just a technical and aesthetic production process. Throughout history, the changing internal dynamics of different periods have led to variations in the definitions of architecture, granting the architect a flexible role that adapts to changing conditions.

This study aims to explore the impact of artificial intelligence on architectural practice, investigate the role and competencies of the new generation architect, and define the scientific and conceptual structure of the transformation the architect has undergone. In this context, understanding the effects of artificial intelligence and digitalization on architectural practice is not only an academic curiosity but also a strategic necessity for the future of the architectural profession. With the new possibilities brought by digitalization, examining how the boundaries of the profession are expanding and defining the concept of new-generation architecture on a scientific basis is among the main concerns of this study. This will highlight the importance of this concept for architectural practice and education.

1. Methodology

This study consists of three main methodological stages aimed at understanding the impact of artificial intelligence (AI) and digitalization on architectural practice and exploring the role of the new-generation architect in this transformation process: literature review, workshop applications, and discourse analysis. The methodology of the study presents a multifaceted research design to understand the effects of digital transformation and AI-based approaches on architectural education and practice.

In the first stage, existing academic studies on the integration of digitalization and AI technologies into architectural practice were examined in detail. The literature review was shaped by studies that investigate the impact of AI on architectural design processes, production methods, and the role of the architect. The studies in the literature emphasize that AI in architecture not only serves for automation but also has the potential to create a new paradigm (Chaillou, 2019; del Campo et al., 2020; Lukovich, 2023). In particular, AI-supported design tools are highlighted as enabling architects to generate more innovative solutions to complex problems and serve as a "co-designer" in architectural design processes, offering new perspectives that humans may not have considered (Borglund, 2022; Cudzik & Radziszewski, 2018). The integration of AI into architectural practice is emphasized as redefining the role of the architect, positioning them in a more strategic and conceptual role (Picon, 2020; Trabucco, 2021). The digital age has transformed architecture, making previously unimaginable new forms of design and construction possible, and allowing architects to analyze and optimize complex geometries and structural systems more effectively (Kolarevic, 2003; M Matter & G Gado, 2024). This transformation process requires architects to acquire new skills and restructure their learning processes. Therefore, the literature review on the use and effects of AI in architecture provides valuable insights into the future of the discipline.

The "Exchange Center" project is a new-generation studio application carried out in the Department of Architecture at Çukurova University in the Fall semester of 2023-2024. The project was implemented to examine the integration of AI into architectural and design processes. The workshop aimed to combine traditional architectural education with digitalization and AI-supported design tools, thereby equipping students with the necessary skills for modern architectural practice. The workshop process was specifically structured to develop students' digital and computational thinking skills in architectural design. This studio, where the concept of exchange was internalized, provides an environment where students could freely create their own architectural programs without using money. In this context, students were first trained with three-dimensional modeling software such as SketchUp and visualized their designs in the digital environment, enabling them to visualize geometric relationships and spaces more effectively. At the beginning of the project, innovative solutions offered by AI were explored, and these tools were integrated into the design process. If the process is structured correctly, this workshop could serve as an effective example of the learning and application methods of new-generation architecture. Accordingly, the "Exchange Center" project can be presented as a methodological approach examining the integration of digitalization and AI into architectural practice. Research techniques such as semi-structured interviews, observations, surveys, and discourse analysis were used during the data collection process. Concepts that emerged in the discourse analysis were examined through thematic analysis.

The data expressed by students both verbally and in writing about the project processes were examined in this stage. Discourse analysis aims to understand students' interactions with digital tools, their learning processes, and their perceptions of architectural practice. This analysis will highlight the prominent concepts and themes related to how AI and digitalization affected students' designs, creative processes, and architectural understanding. The challenges, opportunities, and future expectations that students encountered while combining traditional architectural education with digital tools were explored in-depth through discourse analysis.

2. Artificial Intelligence and Next-Generation Architecture

"We shape our tools, and thereafter our tools shape us."
(Marshall McLuhan; John M. Culkin, 1967: 70; Yılmaz, 2023).

The interaction between technology and architecture has manifested itself in various forms throughout history. With the Industrial Revolution, the widespread use of mechanical production processes and new materials led to significant transformations in architectural practice. During this period, the introduction of mass production and factory methods enabled architects to automate many processes that were previously performed manually, allowing them to carry out design processes more efficiently and quickly. The impact of digitalization became more pronounced from the late 20th century onwards, as architects began to design more complex and free geometric forms using computer-aided design (CAD) software and modeling techniques. These developments caused architecture to evolve from being solely an aesthetic discipline into a data-driven, computational, and simulation-based structure (Kolarevic, 2003). Chaillou (2019) emphasizes that the use of artificial intelligence in architecture is not a sudden shift, but rather the result of 70 years of accumulated progress. He notes that technological transformations in architecture occurred in four main stages: modularity, computational design, parametric design, and finally, artificial intelligence, each of which has transformed architectural practice and offered new possibilities.

2.1. Artificial Intelligence and Digitalization

Artificial intelligence (AI) and digitalization represent one of the most critical turning points in contemporary architecture. Technologies such as algorithms and machine learning have assumed the role of a "co-design partner" in architectural practice, making design processes more efficient and innovative. In particular, AI is used in tasks such as optimizing design parameters and conducting data analytics. Digital tools like Building Information Modeling (BIM) offer a more comprehensive and integrated approach throughout the design and construction phases, enabling architects to manage their projects more quickly and accurately (Picon, 2020).

Beyond merely supporting automation, AI has the potential to create a new paradigm in architecture. AI-based systems are expected to transform architectural practice, contributing to more efficient, creative, and sustainable design processes. While AI will provide architects with greater flexibility and creativity in their design processes, human-centered approaches and aesthetic sensitivity will remain critical (Chaillou, 2019).

With digitalization, architects are not only producing physical forms but are also analyzing the environmental and structural impacts of their designs to build more sustainable and functional structures (Kolarevic, 2003). This process has created a profound transformation in architectural practice, where the integration of AI and digital tools enables more conscious decision-making at every stage. Ploennigs and Berger (n.d.) comprehensively address the potential, current limitations, and future opportunities of AI-based image production tools in architecture. The authors suggest that AI tools can increase efficiency and creativity in architectural design processes, but they have not yet provided complete solutions. These tools, particularly in areas like concept development and interior and exterior design, hold significant potential, and when integrated with Building Information Modeling (BIM) in the future, they could offer more advanced and meaningful design processes (Ploennigs & Berger, n.d.).

Architectural practice largely depends on creative and analytical thinking, unique perspectives, problem-solving abilities, and cognitive skills that technology has yet to fully replicate. AI, by enhancing collaboration between humans and machines, can automate repetitive and routine tasks, allowing architects to focus more on the creative and unique aspects of design (Widyakusuma, 2024).

2.2. Architecture Education and the New Generation Architect

Technological advancements are profoundly impacting architecture education as well. While traditional architecture education focused on hand drawings and physical models, today digital tools and artificial intelligence have become an integral part of the curriculum. However, this transformation also brings some challenges. Trabucco (2021) emphasizes that while architectural education is equipped with technological tools, fundamental skills such as creativity and critical thinking should not be overlooked. Architecture universities can integrate artificial intelligence by altering course contents and the profession's core paradigms, and this integration could result in outcomes beyond the mere combination of human intelligence with computer power, thereby fostering a new perspective for the future (Trabucco, 2021). Del Campo et al. (2021) state that digital tools can be used by designers as instruments that enable them to see the world in a different way, and this new perspective can be employed to inform the design process. Artificial intelligence should not be viewed as a threat, but rather as a powerful ally—a tool that can enhance our skills and help architects reach their full potential (Widyakusuma, 2024). Picon (2020) argues that artificial intelligence will not replace architects but will redefine their role, shifting the focus from technical implementation to conceptual innovation. At this point, the boundaries of the profession and the concept of the new generation architect come to the forefront.

3. Discussion and Results

The data collection process was conducted specifically within the context of the Exchange Center Workshop, using qualitative data collection techniques such as participant observation, semi-structured interviews, and document analysis. The collected data was examined through thematic analysis, revealing themes related to the impacts of artificial intelligence and digitalization on architectural practice (Figure 1). These concepts were then categorized under the themes defined within the context of the process and topic.

It is notable that the boundaries between the themes are not sharp, and they are interrelated. The themes are observed to be interacting with one another (Figure 2). When the themes are grouped under common headings, it is evident that they point to the skill set of the new generation architect (Figure 3).

ETKİLEŞİM	EĞİM	SKETCHUP	TAŞIYICI SİSTEM	İŞ BİRLİĞİ
BİLGİ ALIŞVERİŞİ	**ARAZİYE GÖMÜLME**	**MEKAN ALGISI**	**ÖZGÜR**	**ÖĞRENME SÜRECİ**
BİLGİ TAKASI	PEYZAJ	SÜRDÜRÜLEBİLİR	KENDİNİ KEŞFETME	ZORLUKLAR
STÜDYO	**MAKET**	**ÖZGÜRLEŞME**	**EĞİMLİ ARAZİYİ KULLANMA**	**DOĞAYLA UYUMLU TASARIM**
YAPAY ZEKA	MODEL	ZAMAN YÖNETİMİ	DAYANIŞMA	AĞAÇLARIN KORUNMASI
REVİZE	**ÜÇ BOYUTLU DÜŞÜNME**	**EKSİK YÖNLER**	**GELİŞİM**	**YENİ BECERİLER EDİNME**
SINIRLARI ZORLAMA	YAPAY ZEKADAN DESTEK	BAKIŞ AÇISI	VERİMLİ	3 BOYUTLU TASARIM
KESİTLE ÇALIŞMA	**ÖZGÜRLÜK**	**FARK YARATMA**	**HIZLANMA**	**KRİTİK**
İLHAM	ALTERNATİF ÇÖZÜMLER	KALABALIK	BAĞIMSIZ	KONSEPT
BAKIŞ AÇISI	**ESKİZ**	**DEĞİŞİM**	**ZORLUK**	**YARATICI**

Figure 1: Concepts Analyzed from the Data

Discourse analysis is an important method for understanding how language and linguistic structures are used as tools that convey meaning in the context of society and culture. In this context, the discourse analysis conducted on the "Takas Merkezi" project highlights a significant aspect of the integration of artificial intelligence in architectural practice in the digitized world. The analysis reveals that concepts are grouped under specific themes, and these themes point to the skill set required of the new-generation architect (Figure 4). This finding offers valuable insights into how architectural education is shaping in the digital age.

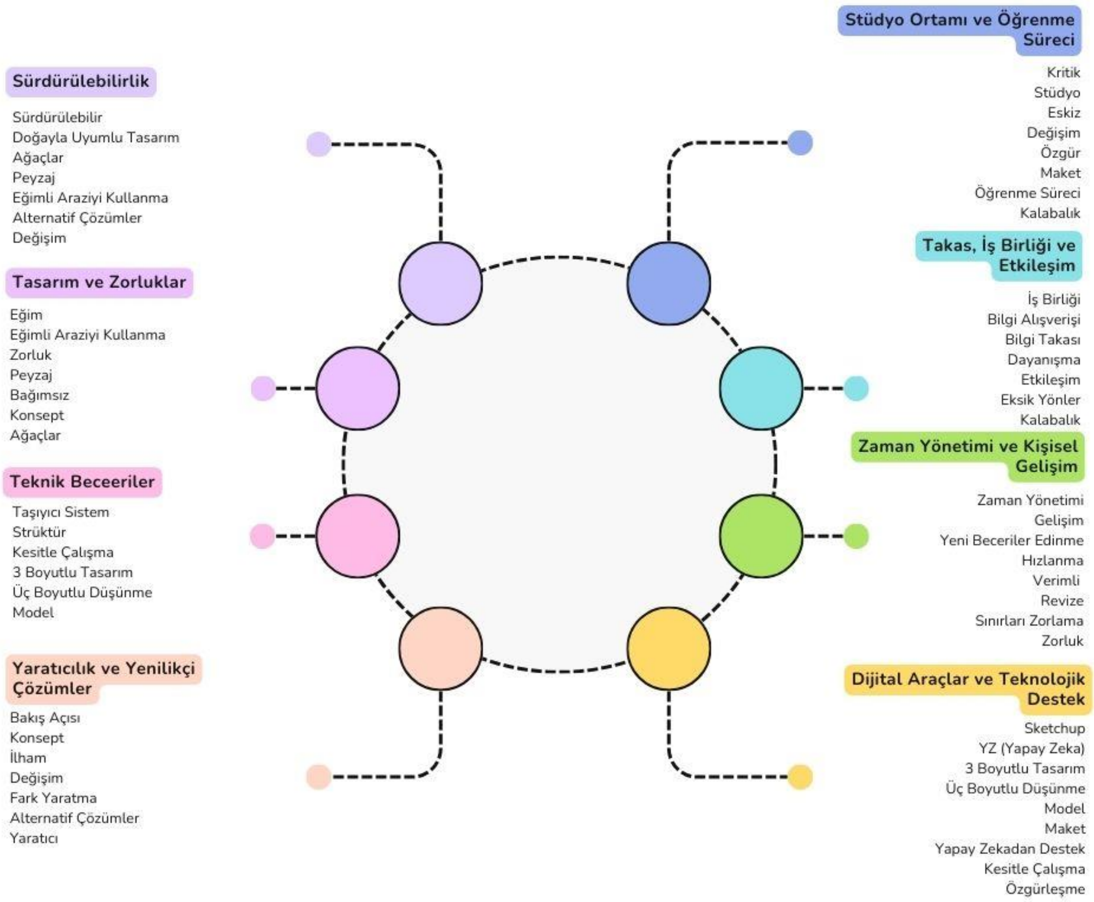

Figure 2: Classification of Concepts under Themes

The key findings of the discourse analysis show that themes related to the integration of digitalization and artificial intelligence into architectural practice are heavily discussed. These themes emphasize the necessity for new-generation architects to develop digital and computational thinking skills, creativity, problem-solving abilities, and technical expertise in their design processes. All of these skills are becoming more pronounced in a digitized world, enabling architects to produce more efficient, creative, and flexible designs. Notably, the use of AI-assisted design tools contributes both a creative dimension to architectural practice and accelerates the design process, improving efficiency.

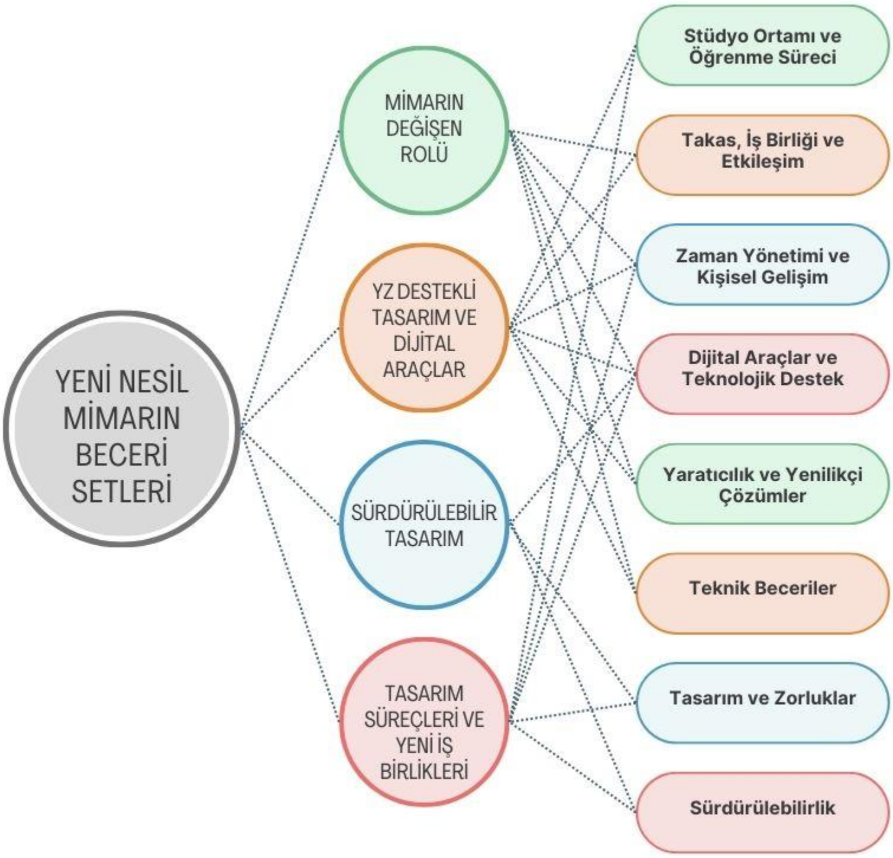

Figure 3: Common Headings Where Themes Merge

The findings suggest that the new-generation architect needs to possess not only technical skills but also strategic and conceptual thinking (Picon, 2020). These findings align with the literature, particularly the idea of positioning artificial intelligence as a "collaborative designer" in architectural practice (Chaillou, 2019), the shift of the architect's role from a "technical implementer" to a "conceptual leader" (Trabucco, 2021), and the need for new skills in architectural education due to digitalization.

Discourse analysis illustrates how the skill sets of the new-generation architect are shaped in the digitized world and how the integration of artificial intelligence into architectural practice transforms these skills. In this context, it appears that architectural education will increasingly focus on digitalization and the fusion of technology with creativity. A curriculum that enables students to develop digital and computational thinking skills and integrate AI tools into their designs will allow architects not only to enhance their technical expertise but also to nurture their creative and aesthetic sensibilities.

Figure 4: Skill Sets of the New Generation Architect

These developments could enable the emergence of more efficient, sustainable, and aesthetically rich designs in the architectural practice of the future. The ability to blend technological advancements with creative approaches is expected to define the new-generation architect, shaping both their professional capabilities and their approach to the built environment.

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BREATHING STRAW BALE WALL SYSTEM

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Abstract

This study presents an innovative, internationally patent-pending passive straw-bale wall and building system that integrates a novel ventilation approach, termed the "breathing wall system".

In many passive house systems and energy-efficient buildings, heating or cooling systems may be unnecessary in moderate climates due to high levels of insulation and optimal building orientation. However, automated ventilation systems with heat recovery are typically indispensable, as such designs emphasize "airtightness," a fundamental principle of 20th-century energy-efficient architecture.

In this context, the term "breathing" does not refer to the conventional 20th-century concept of water vapor permeability in walls but rather to the air permeability of the wall system. The breathing wall system operates through small perforations, approximately one millimeter in radius, located on the façade. These openings facilitate a controlled influx of exterior air into the building interior. The number and dimensions of these perforations are carefully optimized to regulate airflow rate and velocity, thereby maintaining indoor thermal comfort. Additionally, the wall envelope serves as a passive heat recovery system.

Ongoing research involves testing breathing wall systems with various materials, including concrete, timber, and glass, under laboratory conditions and on a small scale. Preliminary findings indicate a significant departure from traditional 20th-century multilayered, air-tight, energy-efficient façades, suggesting a paradigm shift in building envelope design. However, implementing a façade with numerous small perforations presents practical challenges, such as production complexity, susceptibility to dirt accumulation, dust and water infiltration, acoustic vulnerabilities, and condensation risks. These issues must be addressed to facilitate broader adoption.

While conventional building materials have been extensively studied, the potential of straw bales in this context remains largely unexplored. Due to their inherently porous nature, straw bales naturally facilitate airflow. By adjusting the material's thickness and density, it is possible to regulate both the volume and velocity of air passing through the straw. Furthermore, a patented breathing wall apparatus enables the system to function effectively even on rendered surfaces, mitigating risks such as dirt accumulation, rainwater infiltration, and other operational challenges.

Integrating the breathing wall system with a straw-bale construction approach has the potential to significantly reduce or even eliminate reliance on mechanical HVAC systems. This innovation represents a critical advancement toward achieving "zero-energy buildings" and "carbon neutrality" throughout a structure's operational lifespan.

The SBWNV system introduces a pioneering building envelope concept, offering a novel passive climate-control solution for sustainable architecture.

Keywords: *Straw-bale Breathing Wall, Breathing wall, Ventilation, Energy Efficiency in architecture, Zero Energy Building*

1. Introduction

1.1. Evolution of Building Technology: From the 19th to the 21st Century

In the 19th century, building technology lacked automation in heating systems, relying primarily on burning fuel such as wood. The primary goal was heat generation, with no consideration given to active ventilation or cooling systems (Eriksdotter and Legnér 2015). Insulation was virtually non-existent, and building envelopes were typically composed of a single material, such as stone, adobe, or cob. These envelopes were generally single-layered unless an additional render was applied to the interior or exterior surfaces. In load-bearing structures, the wall functioned simultaneously as the material, structural element, and thermal barrier—effectively creating an "all-in-one" system (Figure 1).

The 20th century brought significant advancements in building technology with the introduction of new materials and construction techniques. The development of mechanical heating, cooling, and ventilation systems, alongside an expanded range of building materials, revolutionized the industry. The integration of multiple systems became standard practice, giving rise to more complex structural elements, components, and construction details. Buildings of this era were designed to be insulated from the environment (Moe, 2014). The increasing reliance on automation and software further contributed to this complexity, optimizing both design and construction processes. Building Information Modeling (BIM) became a crucial tool, facilitating interdisciplinary collaboration and coordination. Building physics considered the movement of heat and moisture together through buildings and combined them with the term "hygrothermal" properties of the material, recognizing that heat and humidity do not separate from each other but should be considered and treated as one. (Yarbrough, Bomberg and Zapala, 2018).

During this period, building standards and regulations also evolved, with "energy efficiency" emerging as a fundamental principle of 20th-century architecture. While insulation and airtightness played a key role in energy conservation, they also led to increasingly complex façade systems, where multiple layers performed distinct functions. Mechanical ventilation systems were introduced to regulate indoor air quality by supplying fresh air from outside as needed and mixing it with recirculated interior air. This approach was designed to maintain indoor thermal comfort while minimizing heat loss (Bomberg, Gibson and Zhang 2014).

1.2. The 21st Century: A Shift Toward Simplification and Passive Design

The 21st century marks a shift toward simplification in both building technology and sustainable architecture (Figure 1). The evolution of façade design increasingly mirrors the single material, "all-in-one" envelopes characteristic of the 19th century, albeit with modern performance enhancements. Concurrently, advancements in passive systems and technological innovations have reinforced this trend. For instance, the widespread use of heat pumps, thermal solar panels, heat storage tanks, phase-change materials, and radiant heating-cooling systems has significantly reduced the reliance on fuel-burning systems and eliminated many mechanical components such as vertical and horizontal air shafts and burning chimneys. Solar and geothermal energy are now sufficient for interior heating in many cases. Additionally, integrating radiant heating and cooling systems within structural elements and surfaces has eliminated the need for extensive ductwork and inefficient air-based HVAC systems, thereby reducing the overall demand for ventilation (Moe, 2014).

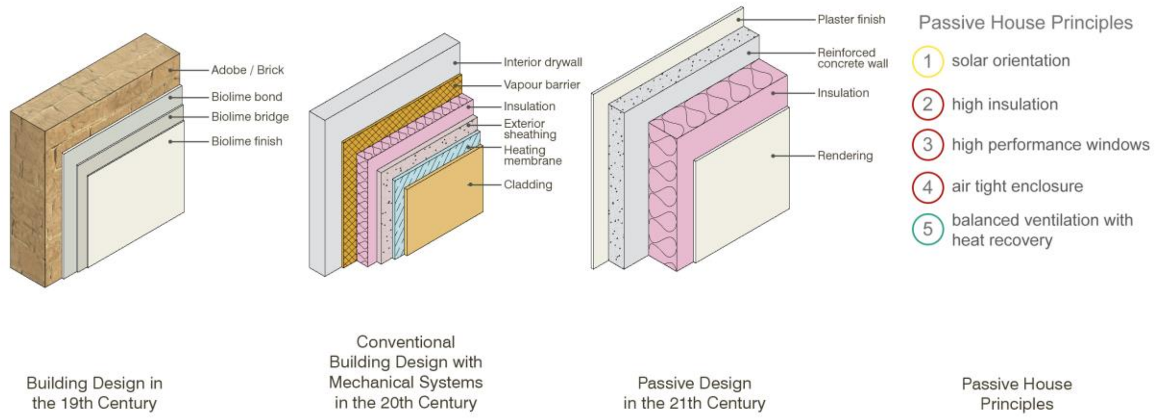

Figure 1: Passive design and its well accepted principles are presented as the final stage of development in the building design history for an ecological building design (Tekin, 2025).

The transformation of façade systems in the 21st century is increasingly evident, with many contemporary designs seeking to replace multi-layered façade systems with single-material envelopes. Straw-bale construction, rammed earth buildings, and other non-insulated structures are reviving the historical concept of "all-in-one" envelopes, albeit with increased thickness to enhance thermal performance. This approach minimizes the need for additional insulation layers, air gaps, vapor barriers, and, in some cases, even finishing materials while still maintaining high energy efficiency. Recent architectural research has explored alternative strategies that prioritize single-layered building envelopes over complex multi-layered systems to achieve "(nearly) zero-energy" performance (Figure 1). Notable examples include Concept 22/26, designed by Lars Junghans and constructed in Lustenau, Austria, in 2016 (Junghans, 2016; Junghans & Widerin, 2017), and the Zollverein School of Management (Sanaa, 2006) (Moe 2010). These projects demonstrate the potential of simplified façade systems in achieving high energy efficiency while simultaneously reducing material complexity.

1.2.1. Passivhaus Principles and the Role of Ventilation

Within this broader context, the Passivhaus building is a leading example of the shift toward reducing dependence on mechanical systems while maintaining high energy efficiency. Passive design strategies are increasingly implemented to ensure indoor thermal comfort with minimal energy consumption. The Passivhaus standard is built upon five fundamental principles:

-Passive heating and cooling through optimized solar orientation,

-High-performance insulation throughout the building envelope,

-Advanced windows and door frames featuring triple or quadruple glazing,

-Airtight enclosures to minimize energy loss, and

-An automated mechanical ventilation system with heat recovery (MVHR) (Chui, 2017) (Figure 1).

Due to their high insulation levels and airtightness, buildings often require little to no active heating or cooling systems, particularly in moderate climates. Internal heat gains from occupants and appliances can be sufficient to maintain indoor thermal comfort. These principles are widely acknowledged and integrated into various energy-efficient building designs, extending beyond the Passivhaus standard (Junghans, Widerin, 2017).

However, although airtightness enhances energy conservation, it necessitates mechanical ventilation to sustain indoor air quality. Human occupants continuously consume oxygen and require a steady influx of fresh air. As a result, mechanical ventilation with heat recovery remains a fundamental component of the Passivhaus system. Fresh air is supplied to the interior while stale air is expelled, ensuring both thermal comfort and air quality (Aganovic, Hamon, Kolarik, Cao, 2017).

Airtightness is applied consistently throughout the building to minimize heat loss and maintain indoor thermal stability. However, mechanical ventilation systems extract a portion of the indoor air and replace it with fresh outdoor air. While this approach is intended to preserve airtightness and optimize energy efficiency, in practice, notable air and energy losses occur during the ventilation process (Craig, 2014).

Airtightness also contributes to a decline in indoor air quality due to oxygen depletion and the accumulation of carbon dioxide. This necessitates air exchange, traditionally facilitated through a heat recovery process in which indoor air is mixed with fresh outdoor air before being recirculated (Aganovic,2017). The COVID-19 pandemic highlighted the risks associated with this practice, particularly in high-occupancy environments such as offices, where ventilation systems were either deactivated or required to circulate 100% fresh air. This, in turn, disrupted the balance between energy efficiency and indoor air quality in buildings.

Consequently, ventilation systems, heat exchangers, and their automation have emerged as the primary energy-consuming components of the Passivhaus system. The Mechanical Ventilation with Heat Recovery (MVHR) system plays a critical role in its operation, accounting for a significant portion of energy consumption (Makarov and Baimachev 2020). Notably, the MVHR system remains the sole major "active" and cost-intensive component within the otherwise passive Passivhaus framework (Figure 1).

2. Breathing Wall Technologies: Evolution and Contemporary Approaches

The objective is to challenge conventional boundaries by transforming active, automated mechanical ventilation and heat exchange processes into fully or partially passive systems that operate with minimal or no energy consumption (Craig, 2014). In response, researchers have explored alternative strategies to reduce energy demand in ventilation systems, with a particular emphasis on breathing wall technologies. While the term "breathing" traditionally denotes vapor permeability in 20th-century building physics, in this context, it specifically refers to the controlled air permeability of the wall.

Several technologies have been developed for breathing wall systems. One method incorporates continuous air channels extending from the floor to the roof, with a designated aperture between the wall layers. In this system, during winter, cold air enters through channels located at the lower section of the wall. As the air moves upward, it undergoes heat exchange due to the thermal properties of the wall material. By the time it reaches the upper sections, it has partially warmed and is then introduced into the interior space (Salah and Imbabi 2012). These first-generation systems align with the multi-layered, multi-material, and highly complex building envelope designs that defined 20th-century architecture. Additionally, the thermal mass properties of the wall contribute to enhancing the overall efficiency of the system.

A second-generation breathing wall technology relies on the integration of numerous small perforations—typically millimeters in diameter—extending through the entire wall thickness or on the use of inherently porous, air-permeable materials such as wood, glass, and concrete. Experimental studies have optimized airflow through these perforations, demonstrating their ability to facilitate effective natural ventilation while preserving indoor comfort conditions. Consequently, this approach theoretically enables the deactivation of mechanical ventilation systems (Figure 2 and 3; Craig, 2021).

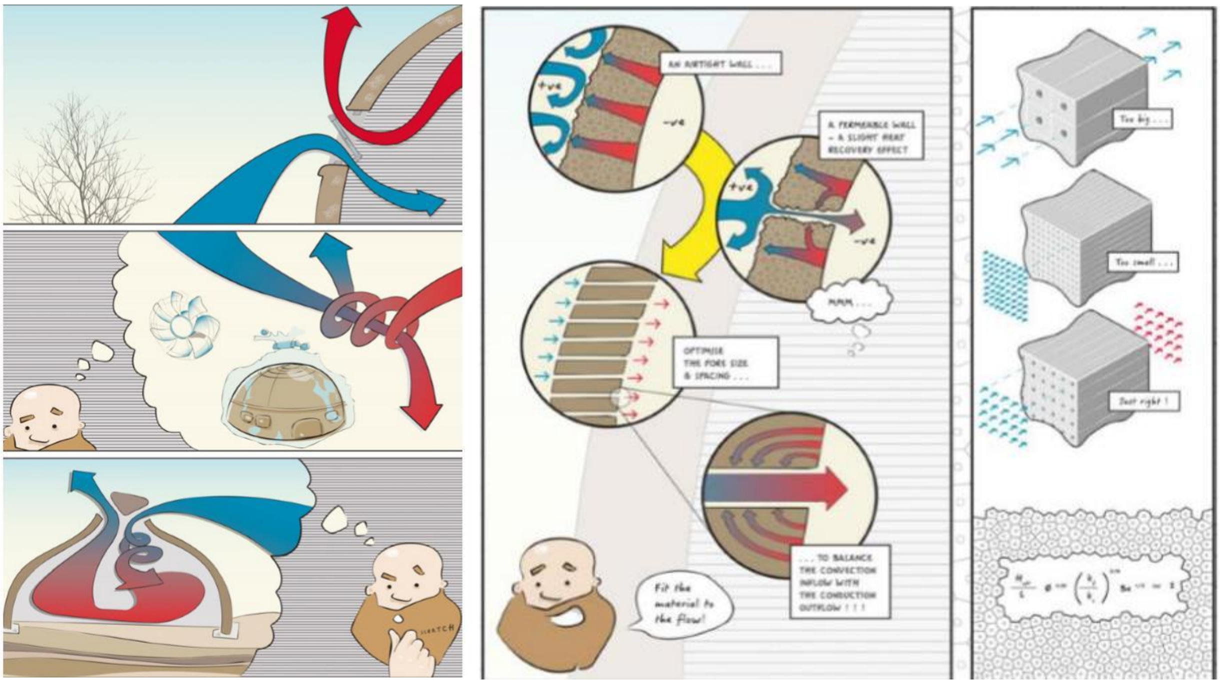

Figure 2: A new breathing wall technology proposal (Craig, 2014, p.273 and 374).

Introducing perforations in the façade to facilitate air infiltration marks a significant paradigm shift, particularly in contrast to the traditional multi-layered, airtight building envelopes of the 20th century.

Aligned with the reductionist architectural trends of the 21st century, contemporary building walls increasingly prioritize multi-functionality and ecological-energy efficiency within a single structural system, thereby minimizing the number of layers. In these designs, air moves laterally across a shorter distance than in first-generation systems. However, the carefully optimized dimensions of the perforations substantially reduce airflow velocity and volume. Despite the reduced air travel distance, the thermal mass properties of the wall continue to support passive heat exchange, albeit at a slower rate (Figure 3).

Following promising laboratory test results, breathing wall systems were first implemented at the building scale for research purposes by Rural Studio at Auburn University. However, challenges such as rainwater infiltration, dust and dirt accumulation within the perforations, and potential acoustic concerns necessitate further technical advancements to enhance the feasibility of this system for broader application (Figure 4; Rural Studio, 2019).

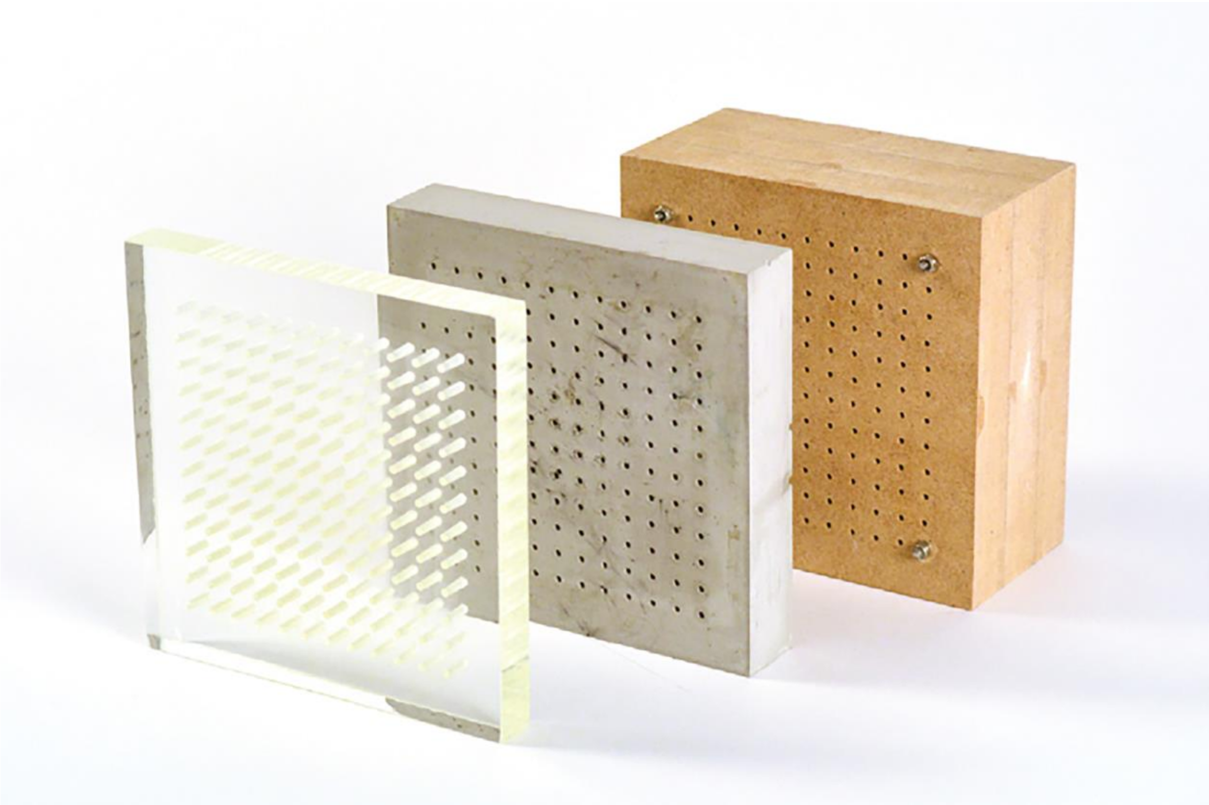

Figure 3: Building envelope with porous material optimized to exchange heat to the incoming air (sucked in by a fan or a chimney) with minimal conduction losses. A water circuit integrated at the interior surface of the panel controls the temperature. Weatherproofing and wind-buffering can be done by an external rain-screen. Glass, timber and concrete perforated test panels (Craig, and Grinham, 2017, p.248).

3. An Innovative Breathing Straw-Bale Wall Design Approach (SBWNV)

The SBWNV international patent pending system seeks to develop a breathing straw wall technology that eliminates the need for mechanical ventilation in passive building designs by offering a passive ventilation alternative (Figure 5). This invention explores the use of straw—a naturally porous, bio-based material—as the primary component of the building envelope. The SBWNV approach evaluates the air permeability of straw to optimize natural airflow, thereby reducing energy consumption in passive design strategies (Saatcıoğlu, 2020).

Figure 4: Rural Studio’s “Breathing wall Mass Timber Research Project” (2019) and its perspective section (Rural Studio, 2019; Craig, 2021).

Although researchers have been exploring and testing the breathing wall concept using various building materials, straw bale has yet to be thoroughly investigated. As a naturally porous material, untreated straw bale inherently facilitates airflow. The volume and velocity of air passing through straw can be regulated by adjusting its thickness and density, offering a controllable means of passive ventilation (Saatcıoğlu, 2020).

The patented system utilizes a simple pipe mechanism to regulate natural airflow. To improve durability and weather resistance, the SBWNV system is preferably coated with lime, which acts as a protective layer for the straw wall. The selection of straw and lime as primary wall materials aligns with a circular design approach, demonstrating a comprehensive application of ecological principles (Figure 6). Moreover, these materials have the potential to substantially reduce CO_2 emissions in the construction industry, thereby contributing to climate change mitigation. Additionally, lime render enhances the thermal mass of the building envelope, further improving passive heat exchange capacity.

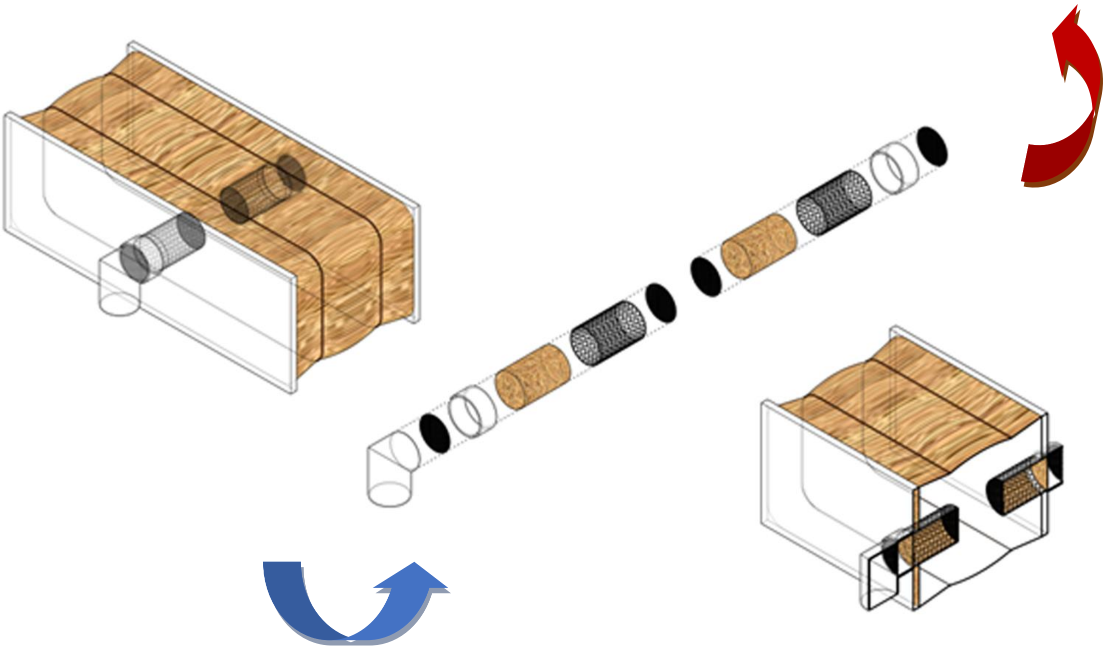

Figure 5: Patented breathing straw bale wall system for passive ventilation (Saatcıoğlu, 2020).

The primary objective of this invention is to develop a wall apparatus that facilitates passive ventilation by directing outside air into the indoor environment through the porous, breathing straw bale material. In conventional bale construction, where straw bales are rendered and densely stacked at approximately 100 kg/m³, natural airflow is significantly restricted (Brojan, Weil and Clouston 2015). The integration of pipes within the straw bale structure allows air to circulate while simultaneously shielding the wall from external environmental factors such as rain and dust (Figure 5).

Circular design, which prioritizes resource reuse and recycling, emphasizes the continuous circulation of materials in various forms, ensuring their reintegration into natural cycles over time. This invention seeks to re-examine one of the core principles of the "passive house" approach by presenting a viable strategy for developing "nearly zero-energy" buildings that function without active heating, cooling, or ventilation systems.

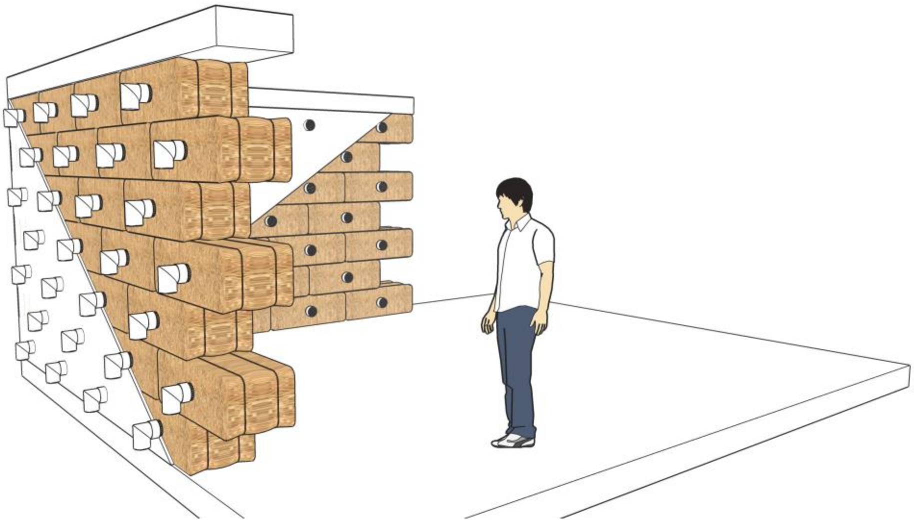

Figure 6: Key design principles are integrated to the all-in one passive breathing straw bale wall**.**

The key design principles of the SBWNV system are as follows:

- **Passive Design:** Utilizing natural building materials to reduce CO_2 emissions associated with construction.
- **Optimizing Energy Use:** Minimizing energy consumption by utilizing natural ventilation and reducing maintenance costs.
- **Circular Design:** Adopting circular economy business models that promote circular design principles. This involves designing an envelope system that eliminates waste and accelerates the transition to a circular economy within the construction industry.
- **Material Potential:** Investigating the air permeability of straw as a potential means of minimizing energy consumption in passive design through the creation of natural ventilation.
- **Design for Simplicity:** Focusing on simple design details and evolving the envelope with a single-layer approach, as opposed to multi-layered, complex envelope systems.
- **Design for Functionality:** Ensuring that all design details are functional, adaptable, and practical. Additionally, optimizing the building's maintenance processes.

Additionally, the SBWNV wall design aims to simplify building envelopes, thereby reducing the complexity of construction systems within the framework of 21st-century building technology and energy-efficient architecture (Figure 7). By leveraging natural ventilation, SBWNV has the potential to significantly minimize or even eliminate the need for automated systems, reducing energy consumption associated with mechanical ventilation in passive design.

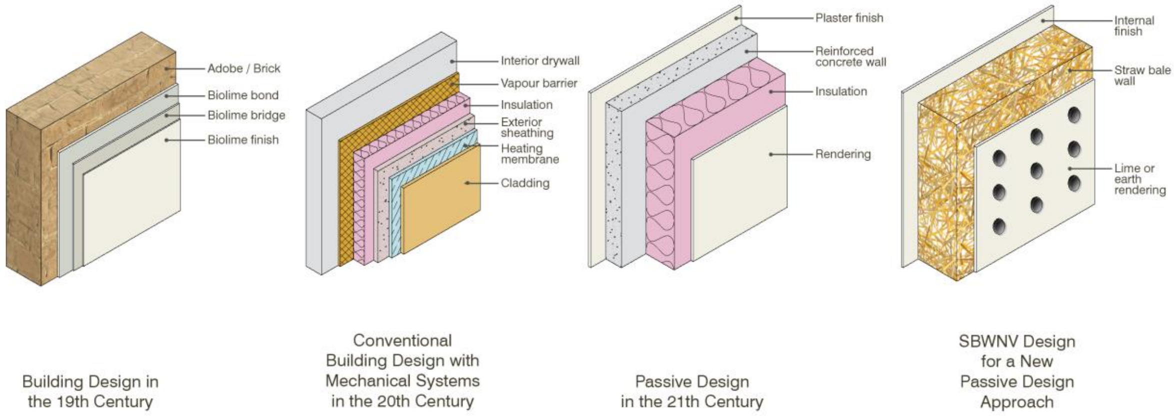

Figure 7: The SBWNV aims to develop an innovative envelope model for circular and passive design as a new technological advancement to reduce environmental impact.

To facilitate natural ventilation and ensure the influx of fresh air, air tubes are incorporated within the wall. The material used for these air tubes is bamboo, a natural resource. The inclusion of air tubes allows for the regulation of air permeability within the wall. Research by Craig and Grinham (2017) suggests the use of millimetric pores on the wall; however, these pores may become obstructed by dust particles during usage. To address this issue, the SBWNV design proposes the use of removable air tubes, which can be cleaned or replaced and maintained.

Straw bales, known for their air-permeable apertures, have been successfully incorporated into building construction techniques. A straw bale is formed by compressing straw stalks and securing them with a polypropylene string, which creates apertures within the bale. When combined with the thickness of the bale, these apertures enhance the material's thermal insulation properties. Experimental studies have shown that straw bales are air permeable (Brojan, Weil and Clouston 2015). However, in high-density compressed, thick and plastered or coated form, straw bale walls are air impermeable. These straw bale walls can achieve the insulation and air-tightness high standards of the "Passivhaus" system easily (Balehaus n.d).

For straw bales to fully realize their potential as a "breathing wall" and be effectively applied in real-world scenarios, it is crucial to develop solutions that permit air passage through the wall surface. This allows for natural and passive ventilation while simultaneously protecting the wall from external weather conditions, such as rain, splash water, and insect infiltration (Saatcioglu, 2020).

The integration of the breathing wall apparatus facilitates natural ventilation in wall configurations by enabling airflow once it transitions inside. The velocity and volume of this airflow can be controlled based on the density of the straw infill material or the straw within the bales. Additionally, the diameter of the air passage can be adjusted to suit specific functions or the need for fresh air (Saatcioglu, 2020).

This design also enables the wall to function as a passive heat exchanger. As air passes through the apertures, it exchanges thermal energy, enhancing the overall energy efficiency of the system. The thermal mass capacity is further influenced by the thickness of both the interior and exterior render, in addition to the straw bale wall itself. In winter conditions, the cold exterior air warms gradually as it travels through the wall, minimizing any sudden temperature drops inside. The slow air velocity, due to the density of the bale, ensures that there is no abrupt loss of heat, maintaining comfort within the interior. Furthermore, the density of the straw bales regulates the amount of air required for ventilation, adapting to the volume and function of the interior space, as determined by the architectural design. This allows for a steady, gradual exchange and renewal of air within the space (Saatcioglu, 2020; Figure 6).

In a conventional Passivhaus system, ventilation and heat exchange are managed through a mechanical and automated process using a Mechanical Ventilation with Heat Recovery (MVHR) system in an airtight interior. However, this system achieves the same outcomes entirely through passive means. Ventilation and heat exchange, instead of relying on an active, energy-intensive process, are converted to a fully or partially passive system, thereby improving energy efficiency and simplifying the mechanical systems required.

The invention offers flexibility in adjusting the airflow required for ventilation. The number of pipes, their diameters, the thickness of the straw within the bales (around the pipes), and the density of the straw can all be optimized and modified according to factors such as climate, building function, or the specific orientation of the wall (e.g., south or east façade). Additionally, the pipes can be replaced or adjusted to accommodate seasonal variations in ventilation needs (Saatcıoğlu,2020).

4. Conclusion

In conclusion, 21st-century building technology and energy-efficient sustainable architecture are increasingly oriented toward simplification. Active systems are progressively being replaced with passive alternatives, driving building materials and construction methods toward greater efficiency and reduced complexity. The breathing wall system, by introducing perforations in the façade, fundamentally challenges the conventional understanding of the multi-layered, airtight façades of the 20th century, marking a significant paradigm shift.

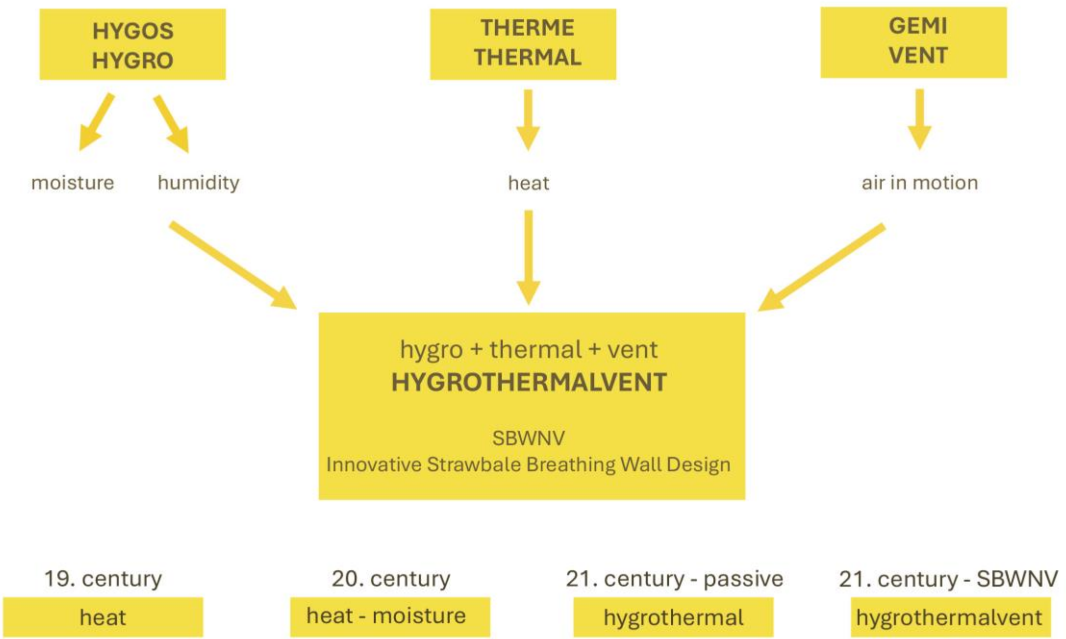

Figure 8. 'Hygrothermalvent' is a newly introduced term in this conference paper, referring to the combined processes of heat transfer, moisture regulation, and airflow dynamics.

This concept necessitates a reinterpretation of building physics to simultaneously address heat transfer, moisture regulation, and airflow dynamics, potentially leading to the introduction of a new term: *hygrothermalvent* (Figure 8). Additionally, carbon footprint assessments in architecture further emphasize the advantages of natural, bio-based materials such as straw, which inherently stores carbon. The Innovative Breathing Straw-Bale Wall Design not only contributes to carbon-neutral architecture but also aspires to achieve a fully zero-energy design—operating without heating, cooling, or ventilation systems. By eliminating mechanical components entirely in moderate climates, this approach advances a fully passive and sustainable building model that holds significant potential for widespread application in the near future.

5. Acknowledgements

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Integration of Multi Criteria Decision-Making Approaches with Life Cycle Assessment: A Systematic and Bibliometric Analysis for Sustainable Material Selection

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Abstract

The integration of sustainability into the built environment has become a critical priority for mitigating environmental impacts, enhancing resource efficiency, and addressing climate change. In this context, the combined use of Life Cycle Assessment (LCA) and multi-criteria decision-making (MCDM) approaches plays a pivotal role in enabling comprehensive evaluations for sustainable material selection. While LCA provides a scientific and systematic basis for assessing the environmental performance of building materials throughout their life cycle, MCDM techniques complement this analysis by incorporating economic, social, and performance-based factors into the decision-making process. The integration of these methodologies allows for more balanced and informed material choices in architecture and construction practices. This study aims to conduct a comprehensive analysis of MCDM approaches integrated with LCA, focusing on their application in sustainable material selection. A bibliometric and systematic review has been performed using the Web of Science Core Collection and Scopus databases. The study evaluates the use, advantages, and limitations of various MCDM methods such as AHP, FAHP, TOPSIS, and others within the context of LCA-based assessments. The bibliometric analysis identifies current research trends, influential studies, key methodologies, recurring keywords, leading contributors, and geographical distribution in the field. The findings provide valuable insights into the evolving research landscape and underline the importance of integrating MCDM with LCA to achieve more effective and sustainable material decisions. This study contributes to the literature by highlighting existing research gaps and offering suggestions for future work that will support environmental, economic, and social sustainability objectives in the construction sector.

Keywords: *Life cycle assessment, decision-making, sustainable material selection*

1. Introduction

As a major contributor to energy consumption, carbon emissions, and the depletion of natural resources, the construction sector plays a significant role in global environmental challenges. The adoption of sustainable strategies aimed at minimizing environmental impacts—particularly through material selection—is essential to addressing these challenges. Life Cycle Assessment (LCA) has emerged as a fundamental methodology for quantifying the environmental performance of building materials across all life cycle stages, including raw material extraction, manufacturing, transportation, use, and end-of-life processes (ISO 14040, 2006; ISO 14044, 2006; Yardimci et. al., 2024).

While LCA provides a robust scientific basis for environmental assessment, it is limited in offering practical decision-making guidance when multiple, often conflicting criteria must be considered—such as cost, durability, environmental footprint, and social implications. Therefore, integrating LCA with Multi-Criteria Decision-Making (MCDM) approaches becomes essential for a more comprehensive and balanced evaluation. This integration enables decision-makers to systematically incorporate environmental, economic, and social parameters into the material selection process. In this way, LCA and MCDM complement each other: LCA offers environmental depth, while MCDM brings structured prioritization to complex choices, ensuring more effective implementation of sustainability principles in architectural and construction practices.

2. Background

With the increasing focus on sustainability in the construction sector, there has been a significant rise in studies integrating Life Cycle Assessment (LCA) with Multi-Criteria Decision-Making (MCDM) approaches. These methodologies play a critical role in assessing the environmental, economic, and social impacts of material selection across all life cycle stages of buildings. While LCA offers a systematic framework for evaluating environmental performance, MCDM techniques support decision-makers by incorporating diverse criteria into the selection process.

Recent research has emphasized the need for both systematic and bibliometric analyses to better understand how LCA and MCDM methods are applied in the context of sustainable material selection. Such analyses are useful for identifying research trends, dominant methodologies, and existing knowledge gaps. Many of the existing studies in the literature tend to focus on specific decision-making techniques or are limited to case-based evaluations. This study aims to contribute by offering a more comprehensive perspective that combines bibliometric and systematic analyses, evaluating the integration of LCA and MCDM methods in terms of methodological diversity, areas of application, and observed limitations.

Accordingly, a bibliometric analysis was conducted based on publications indexed in the Web of Science Core Collection and Scopus databases. This study identifies key publications, recurring keywords, leading contributors, and geographical trends in the field. In addition, a systematic literature review explores how decision-making techniques are applied in sustainability assessments within the architecture and construction sectors. By synthesizing the findings from these analyses, this study provides insight into the effective integration of LCA with decision-support methods and contributes to building data-driven and structured frameworks for sustainable material selection.

3. Material and Method

Stage 1 Definition	**Web of Science databases [n=5497]**	**Scopus databases [n=5919]**
	"life cycle assessment" AND "decision" AND “building” [n=2034]	"life cycle assessment" AND "decision" AND “building” [n=1968]
	"LCA" AND "decision" AND “building” [n=1036]	"LCA" AND "decision" AND “building” [n=1074]
	"life cycle assessment" AND "decision" AND “construction” [n=1608]	"life cycle assessment" AND "decision" AND “construction” [n=1885]
	"LCA" AND "decision" AND “construction” [n=819]	"LCA" AND "decision" AND “construction” [n=992]
Stage 2 Screening	**Related scientific studies [n=5380]**	**Related scientific studies [n=5736]**
	"life cycle assessment" AND "decision" AND “building” [n=1984]	"life cycle assessment" AND "decision" AND “building” [n=1873]
	"LCA" AND "decision" AND “building” [n=1010]	"LCA" AND "decision" AND “building” [n=1023]
	"life cycle assessment" AND "decision" AND “construction” [n=1578]	"life cycle assessment" AND "decision" AND “construction” [n=1885]
	"LCA" AND "decision" AND “construction” [n=808]	"LCA" AND "decision" AND “construction” [n=955]
	Related scientific studies [n=3701]	**Related scientific studies [n=5272]**
	"life cycle assessment" AND "decision" AND “building” [n=1317]	"life cycle assessment" AND "decision" AND “building” [n=1722]
	"LCA" AND "decision" AND “building” [n=786]	"LCA" AND "decision" AND “building” [n=968]
	"life cycle assessment" AND "decision" AND “construction” [n=1005]	"life cycle assessment" AND "decision" AND “construction” [n=1674]
	"LCA" AND "decision" AND “construction” [n=593]	"LCA" AND "decision" AND “construction” [n=908]
Stage 3 Combine	Elimination of duplicate and inappropriate studies [n=602]	Elimination of duplicate and inappropriate studies [n=1691]
	LCA and BIM keywords that are appropriate for studies [n=2293]	
	Elimination of duplicate studies [n=1637]	
Stage 4 Relevance	Elimination of off-topic, not fully relevant studies [n=652]	
	Elimination inappropriate studies [n=153]	
Stage 5 Systematic review	**Studies chosen for systematic literature review [n=86]**	

Table 1: Flows chart of research.

In this study, a bibliometric analysis was carried out of scientific studies that focus on life cycle and decision-making methods in the analysis of buildings. Among these studies, multi-criteria decision-making (MCDM) methods were examined in detail, and research focusing on building material selection using MCDM approaches was systematically reviewed. Bibliometric analysis was carried out using a tool called Bibliometrix, developed in R, a programming language widely used for statistical calculations and graphical analyses (Aria&Cucurullo, 2017).

The selection of appropriate research databases is crucial to ensure the accuracy of bibliometric analyses and the evaluation of scientific literature. In the present study, the Web of Science Core Collection (WoS) and Scopus databases have been selected because they are widely accepted and suitable for various research objectives. These databases are among the largest and important cited databases and are therefore indispensable in bibliometric studies (Qian, 2014; Zhu&Liu, 2020; Moutik, 20-23). For this reason, both bibliometric and systematic reviews were conducted using the Web of Science Core Collection and Scopus. The research flow diagram illustrating this selection process is shown in Table 1.

4. Bibliometric analysis

The selected studies for the bibliometric analysis were evaluated based on their distribution over the years, publication sources, publication locations, the number of publications by authors, the most cited studies, the most relevant keywords, and the most popular frequencies keywords.

4.1. Years of publications

An analysis of the number of studies shows that no significant momentum was observed until 2012. However, after 2012, there was a notable increase in the number of studies, indicating that the selected topics remain current and relevant in the literature. The distribution of scientific studies over the years is illustrated in Figure 1.

4.2. Publication source

When we examined the number of publications, it was found that the most numerous publications were in Journal of Cleaner Production, Sustainability, Building and Environment, Energy and Buildings and International Journal of Life Cycle Assessment. The most relevant sources is shown in Figure 2.

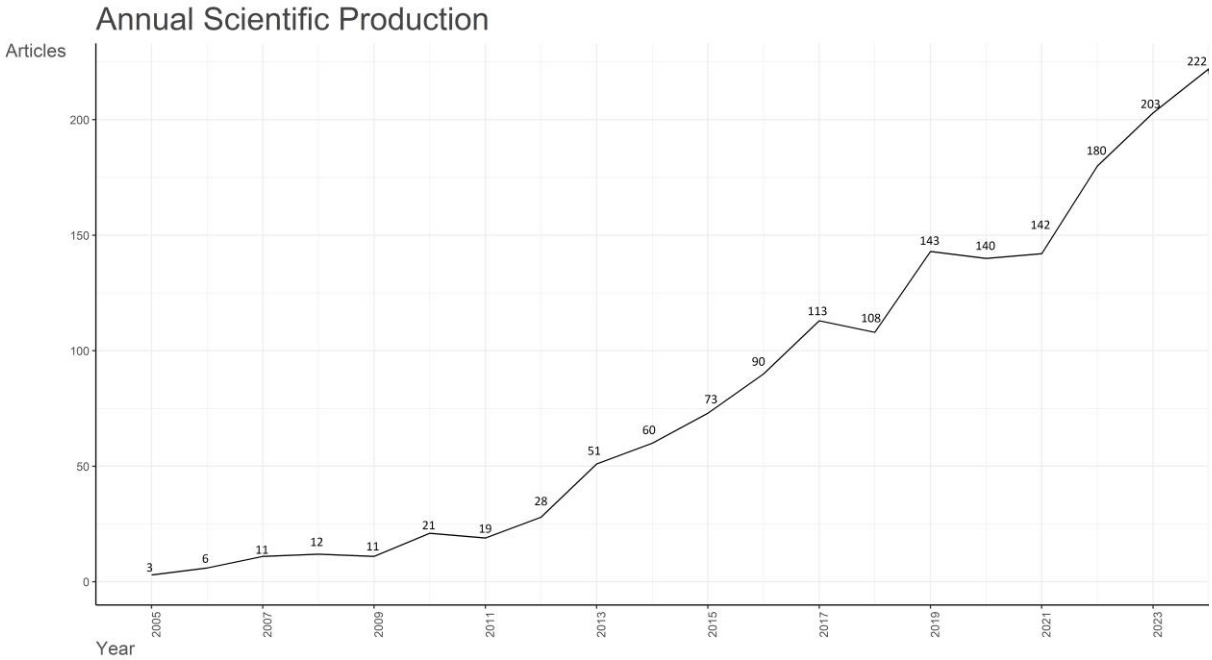

Figure 1: Distribution of the number of scientific studies by annually.

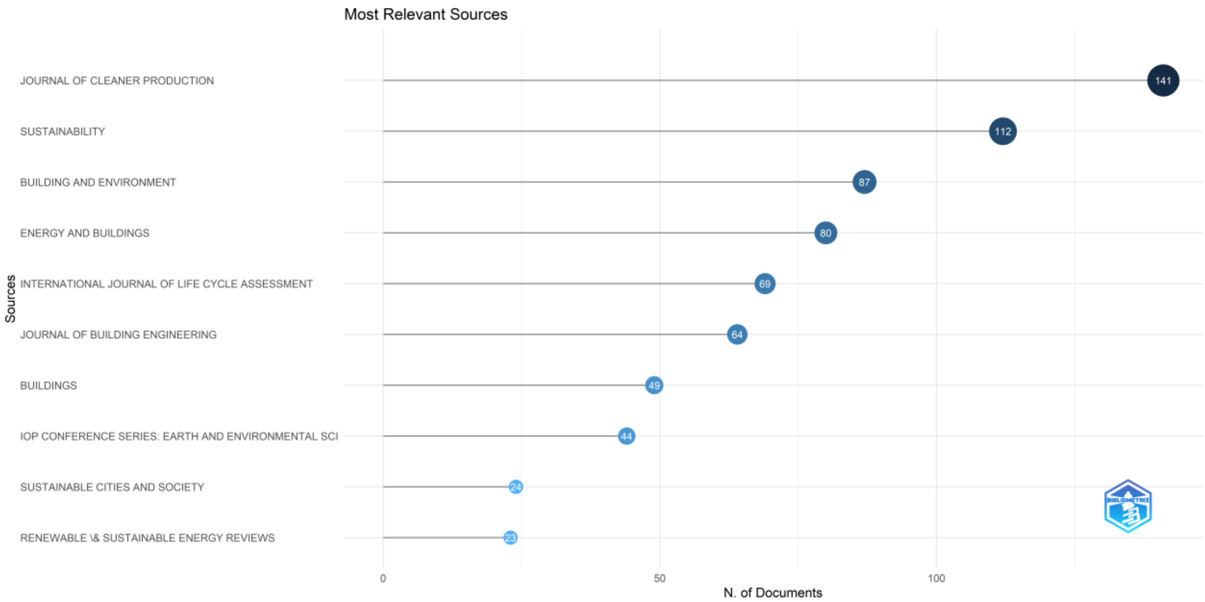

Figure 2: Most relevant sources

4.3. Location of publications

An analysis of the distribution of studies by country reveals that China (457) and the United States (436) stand out among other countries. These are followed by Spain (316), Italy (279), the United Kingdom (240), Australia (232), Germany (195), Canada (182), Portugal (153), and Belgium (132). A darker color tone represents a higher concentration of studies, while lines indicate collaboration between countries. Figure 3 illustrates the distribution of studies by country.

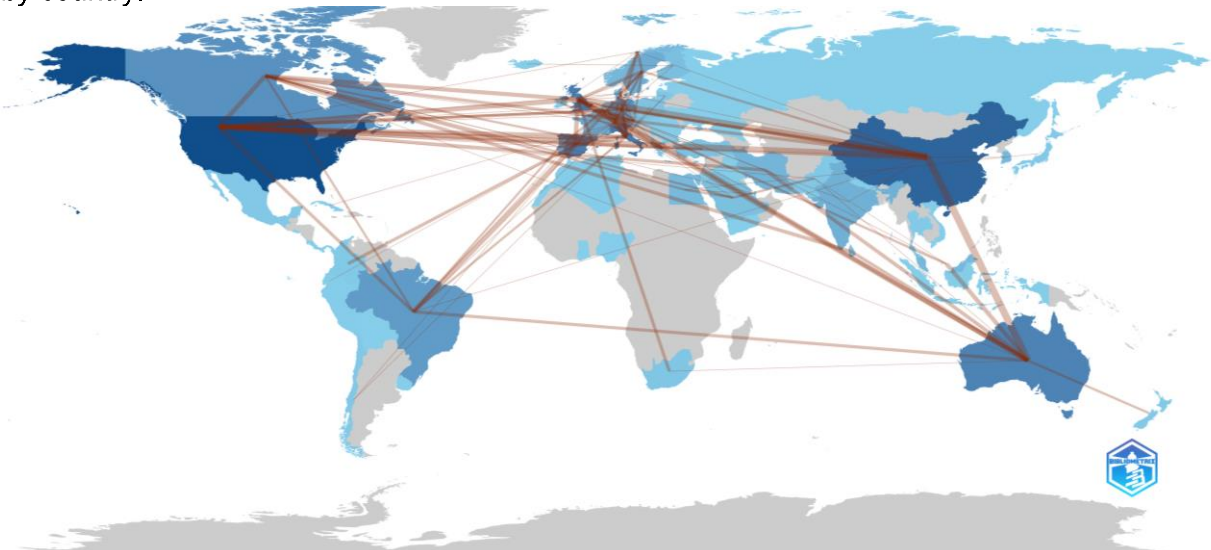

Figure 3: The country distribution of the studies

4.4. Number of publications by author

Among the analyzed studies, some authors have been observed to have a higher number of publications than others. Guillaume Habert is the most prolific author, with 26 publications. Other notable authors with the highest number of studies include Karen Allacker, Kasun Hewage, and Rehan Sadiq. An analysis of publication fractions indicates that Karen Allacker has made the most significant contribution as an author. This suggests that her influence on the analyzed studies is greater than that of other authors. Table 2 presents the number of scientific publications for each author.

4.5. Most cited studies

Table 3 presents the citation numbers of the analyzed scientific studies. The table includes 20 studies, of which 11 are comprehensive literature reviews, and 9 are case studies. Among these, 3 studies were conducted before 2013, while 17 studies were published after 2013.

Authors	Articles	Articles Fractionalized
HABERT G	26	6,538492063
ALLACKER K	23	7,067857143
HEWAGE K	21	5,167857143
SADIQ R	19	4,667857143
HOLLBERG A	18	4,111544012
YEPES V	18	5,616666667
SILVESTRE J	16	3,851190476
BIRGISDOTTIR H	14	2,760714286
CRAWFORD R	14	5,166666667
HONG T	14	3,683333333
LANG W	14	3,001923077
NG S	14	4,295238095
BIRKVED M	12	3,201190476
HADDAD A	12	3,292857143
LEPECH M	12	4
PASSER A	12	2,336544012
SANDANAYAKE M	12	2,933333333
ZHANG G	12	2,492857143
BALASBANEH A	11	4,366666667
FREIRE F	11	3,583333333

Table 2: The number of studies of the authors

4.6. The most relevant words

An analysis of the most relevant keyword groups used in the studies reveals that “life cycle assessment,” “energy,” “construction,” “environmental impact,” “buildings,” “LCA,” “design,” “life cycle,” “decision making,” and “sustainable development” are the most prominent terms. The word cloud in Figure 4 visualizes the relevant keyword groups found in the studies. Larger words represent the most frequently used keywords, while smaller words indicate less commonly used terms.

4.7. The most frequencies words

An analysis of keyword frequencies reveals that in recent years, the terms “sustainable building,” “mortar,” “greenhouse gas emissions,” “circular economy,” “building information modeling,” and “case studies” have been among the most influential keyword groups. Examining the frequency of studies conducted in the last five years, the most recurring keywords include “life cycle,” “decision making,” “environmental impact,” “energy,” “construction,” “design,” “life cycle assessment,” “LCA,” and “emissions.” The widespread use of these keywords in studies and their continuing relevance in recent years indicate that these topics remain current and that various research articles have been published under these themes. Figure 5 illustrates the frequency distribution of these keywords.

Author	Paper name	Total Citations
Chau et. al (2015)	A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings	705
Khasreen etç al. (2009)	Life-cycle assessment and the environmental impact of buildings: a review	582
Haapio& Viitaniemi (2008)	A critical review of building environmental assessment tools.	448
Basbagill et. al. (2013)	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	424
Yeheyis et. al. (2013)	An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability.	368
Labonnote et. al. (2016)	Additive construction: State-of-the-art, challenges and opportunities	348
Anand & Amor (2017)	Recent developments, future challenges and new research directions in LCA of buildings: A critical review	337
Vilches et. al. (2017)	Life cycle assessment (LCA) of building refurbishment: A literature review	293
Mardani et. al. (2017)	A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency.	244
Gursel et. al. (2014)	Life-cycle inventory analysis of concrete production: A critical review.	233
Sala et. al. (2013)	Life cycle sustainability assessment in the context of sustainability science progress (part 2).	229
Hoogmartens et. al. (2014)	Bridging the gap between LCA, LCC and CBA as sustainability assessment tools.	220
Tian et. al. (2018)	Green decoration materials selection under interior environment characteristics: A grey-correlation based hybrid MCDM method.	209
Li et. al. (2010)	An LCA-based environmental impact assessment model for construction processes.	209
Turner et. al. (2015	Greenhouse gas emission factors for recycling of source-segregated waste materials.	201
Cuéllar-Franca& Azapagic	Environmental impacts of the UK residential sector: Life cycle assessment of houses.	199
Röck et. al. (2018)	LCA and BIM: Visualization of environmental potentials in building construction at early design stages.	192
Eleftheriadis et. al. (2017)	Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities.	177
Dahlbo et. al. (2015)	Construction and demolition waste management–a holistic evaluation of environmental performance.	177
Collinge et. al. (2013)	Dynamic life cycle assessment: framework and application to an institutional building.	175

Table 3: The number of citation

5. Systematic literature review

In the systematic literature review, 86 scientific studies were analyzed to examine the multi-criteria decision-making (MCDM) methods used. The number of occurrences of these methods is presented in Table 4. It was determined that the Analytical Hierarchy Process

(AHP) was the most frequently used decision-making method (31), followed by TOPSIS (27), FAHP (11), MIVES (10), and VIKOR (9) as the other most commonly utilized methods.

Figure 4: The most relevant words

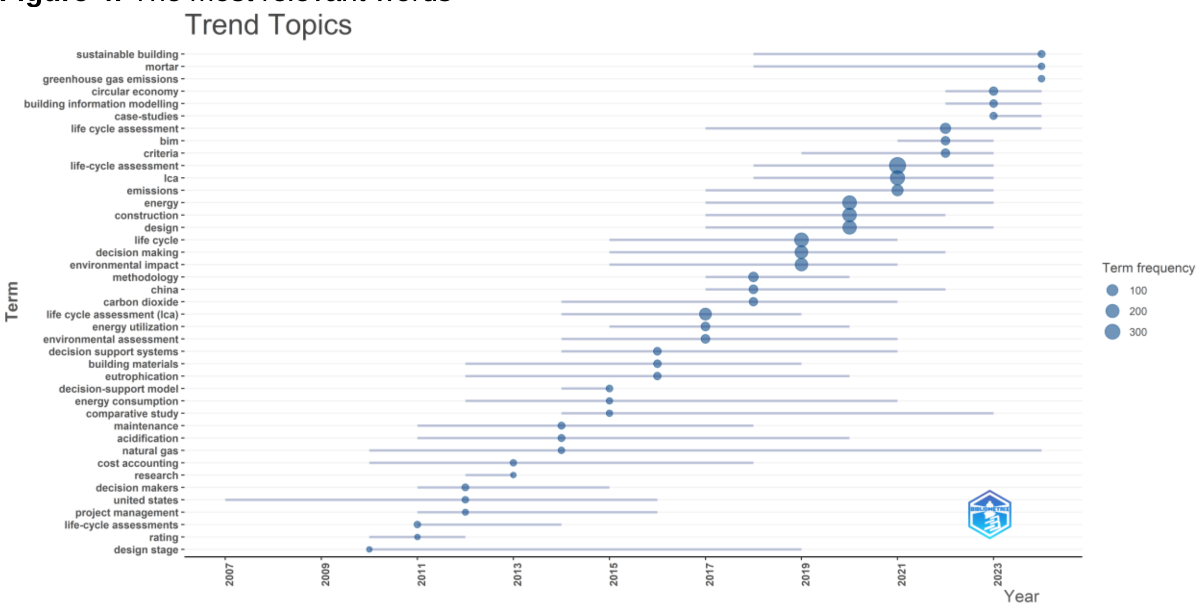

Figure 5: Most frequencies words

Multi-criteria decision-making methods	Number
AHP	31
Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	27
FAHP	11
MIVES	10
VIKOR	9
DELHİ METHOD	4
ANP The analytic network process	3
SWARA	3
ELECTRE methods	3
COPRAS	3
PROMETHEE methods	2
ITARA	2
EDAS	2
SAW	2
Fuzzy Logic	2
TAHP	1
WASPAS	1
DEMATEL	1
ISM	1
MICMAC	1
MAUT	1
AECIEI	1
AHC	1
FUCOM	1
MARCOS	1
FUZZY TOPSIS	1

Table 4: The number of MCDM methods

An analysis of the 86 selected studies reveals that the most frequently researched topics include sustainable material selection (26), sustainable building component selection (18), selection of demolition waste management alternatives (10), selection of building design alternatives (11), and structural system selection (9). The topic distribution of the studies selected for the systematic literature review is presented in Table 5.

Publication topics	Number
Sustainable material selection	26
Sustainable building component selection	18
Selection of demolition waste management alternatives	10
Selection of building design alternatives	11
Structural system selection	9
Selection of material component ratios	7
Building energy optimization	4
Sustainable building selection	4
Ranking of parameters affecting carbon emissions	2
Selection of seismic strengthening alternatives	1
Selection of non-disaster-resistant buildings	1

Table 5: The number of publication topics

5.1. MCDM Studies on Material Selection in Buildings

The systematic review included 26 studies that applied various MCDM methods to support sustainable material selection in the architecture and construction sectors. These studies were analyzed and grouped based on the primary decision-making method employed. Table 6 presents a summary of the reviewed works, categorized by the applied MCDM technique, the number of studies, authors, and their main focus areas. In the following paragraphs, the studies are discussed in detail, organized according to the six main decision-making approaches identified in the review.

MCDM Method	Number of Studies	Studies	Main Focus Areas
AHP	7	AlJalal et al. (2023); Al Shouny et al. (2023); Maaze & Shrivastava (2023); Mayhoub et al. (2021); Sahlol et al. (2021); Habibi et al. (2020); Figueiredo et al. (2021)	HVAC and façade system selection, concrete optimization, alternative brick analysis
FAHP	4	Fernando et al. (2024); Filho et al. (2022); Bostancioglu (2021); Figueiredo et al. (2021)	Cement type evaluation, social sustainability indicators, low-cost housing material selection
TOPSIS	6	Kim & Hammad (2024); Di Ruocco et al. (2022); Yardimci & Kurucay (2024); Balasbaneh & Sher (2024); Streimikiene et al. (2020); Li et al. (2010)	Insulation ranking, material waste reduction, timber product comparison, façade alternatives
VIKOR	3	Alam Bhuiyan & Hammad (2023); Kosanović et al. (2021); Vitorio Junior et al. (2022)	Sustainable housing projects, circular design strategies, social housing comparison
MIVES	3	Sadrolodabaee et al. (2022); Habibi et al. (2020); Gilani et al. (2022)	Green façade assessment, recycled concrete material evaluation, educational building envelopes
Others	3	Naseer et al. (2024); Tighnavard Balasbaneh et al. (2024); Labonnote et al. (2016)	Modular building design, value-based material selection, additive construction technologies

Table 6: MCDM studies on material selection in buildings

Studies using the AHP method have primarily focused on the evaluation of structural components, façade systems, and masonry materials within the context of LCA and LCC integration. AlJalal et al. (2023) developed a decision-making framework that integrates LCC, LCA, and MCDM to evaluate façade and HVAC systems in residential buildings using AHP and MAUT. Their study considered 37 criteria and 28 material alternatives, applying Monte Carlo simulation and efficient frontier analysis for risk assessment. Al Shouny et al. (2023) proposed a fuzzy AHP-based model for sustainable concrete selection in Egypt and Saudi Arabia, highlighting compressive strength and water absorption as critical factors. Maaze and Shrivastava (2023) assessed alternative brick materials through AHP, identifying recycled geopolymer bricks as the most sustainable. Mayhoub et al. (2021) evaluated green cladding materials using AHP and sensitivity analysis, emphasizing indoor air quality and resource conservation. Habibi et al. (2020) applied MIVES and AHP to assess green façades, integrating Delphi method for criteria weighting. Figueiredo et al. (2021) used AHP in a BIM-LCSA framework to evaluate concrete, steel, and wood, finding concrete safest and steel most recyclable.

FAHP-based studies have mostly addressed the selection of cement and insulation materials, emphasizing social sustainability and housing affordability. Fernando et al. (2024) introduced a FAHP-based framework for evaluating cement alternatives, focusing on social sustainability. Their study concluded that CEM II/B-M cement had the highest social score. Filho et al. (2022) integrated FAHP with BIM and TBL indicators for low-income housing, identifying precast concrete, acrylic paint, and fiber cement tiles as top options. Bostancioglu (2021) utilized FAHP to assess green insulation strategies. Figueiredo et al. (2021), in addition to AHP, also employed FAHP elements in combining system dynamics and expert-defined sustainability criteria.

Studies employing the TOPSIS method have mainly investigated insulation performance, façade systems, and comparative analysis of wood-based materials using environmental and economic criteria. Soust-Verdaguer et al. (2024) developed the Smart BIM3LCA tool that integrates TOPSIS with BIM for early design-stage material selection. Kim and Hammad (2024) proposed a DSS using TOPSIS and Pareto search to rank insulation materials based on LCA and LCC. Yardimci and Kurucay (2024) applied TOPSIS with LCA in a BIM-based system to evaluate material waste and environmental performance. Di Ruocco et al. (2022) combined TOPSIS with COMPROMISE methods to assess façade materials by embodied carbon. Balasbaneh and Sher (2024) used both AHP and TOPSIS to compare three timber systems (CLT, NLT, DLT), identifying DLT as the most cost-effective and environmentally efficient. Streimikiene et al. (2020) applied interval TOPSIS to assess insulation materials, concluding recycled glass and sheep wool were most sustainable.

The VIKOR method has been applied in studies exploring user preferences, circular economy principles, and alternative housing strategies for façade and structural materials. Alam Bhuiyan and Hammad (2023) combined AHP, TOPSIS, and VIKOR in a DSS to evaluate materials based on user preferences and four sustainability pillars, identifying wood as the most balanced material. Kosanović et al. (2021) used VIKOR to assess façade retrofit scenarios aligned with circular economy principles, focusing on cost, functionality, and innovation. Vitorio Junior et al. (2022) also employed VIKOR in evaluating sustainable construction alternatives in housing projects.

MIVES-based research has concentrated on the environmental and functional evaluation of façade materials, particularly in educational and residential buildings. Sadrolodabaee et al. (2022) assessed fiber cement panels reinforced with recycled textile waste for façade applications, measuring fire, thermal, and acoustic performance. Habibi et al. (2020) used MIVES in combination with AHP and Delphi for green façades in educational buildings, applying sensitivity analysis for weighting. Gilani et al. (2022) conducted a MIVES-based evaluation on sustainability criteria in envelope systems, focusing on environmental and functional performance.

Studies categorized under other MCDM techniques—such as PROMETHEE, SWARA, and WASPAS—have addressed modular construction, value-based selection, and early-stage material decisions. Tighnavard Balasbaneh et al. (2024) used PROMETHEE to assess sustainability in modular building materials, ranking timber highest environmentally, concrete economically, and steel socially. Nasser et al. (2024) applied SWARA and WASPAS in a BIM-based decision support system for façade materials, achieving over 80% expert consensus. Labonnote et al. (2016) proposed a value engineering-based system for early-phase material selection using hybrid decision techniques.

In summary, the reviewed studies demonstrate the diversity of MCDM methods and their ability to integrate environmental, economic, and social considerations in material selection processes. While each method offers specific advantages depending on project scope and decision criteria, the overall trend highlights a growing emphasis on combining quantitative sustainability metrics with structured decision support. The classification and synthesis provided in this section offer a comprehensive overview of the field and reveal key methodological patterns.

6. Conclusion

This study highlights the crucial role of integrating Life Cycle Assessment (LCA) with multi-criteria decision making approaches to enhance sustainable material selection in the construction sector. Through the integration of bibliometric and systematic analyses, this research provides a comprehensive understanding of how LCA methodologies are being utilized and improved through multi-criteria decision-making frameworks. The findings emphasize that while LCA serves as a robust environmental assessment tool, its full potential is realized when integrated with decision-support methodologies, ensuring a balance between environmental, economic, and social sustainability factors.

Future studies should focus on expanding the scope of LCA applications by incorporating dynamic and real-time data analytics. The integration of digital tools, such as Building Information Modeling (BIM) and digital evaluation frameworks, could further enhance the accuracy and applicability of LCA-based decision-making. Moreover, efforts should be made to standardize data collection methodologies and improve the interoperability of LCA databases across different regions and industries. Additionally, interdisciplinary research should be encouraged to bridge the gap between environmental science, engineering, and policy-making. More case studies are needed to evaluate the practical implications of integrating LCA with decision-making tools in real-world construction projects. These studies should address key challenges such as data accessibility, regional variations in material performance, and regulatory frameworks. Ultimately, enhancing LCA-based decision-making will require continuous innovation in assessment methodologies and the development of user-friendly decision-support systems. Future research should explore how LCA can be further embedded into early-stage design processes to facilitate proactive sustainability assessments. As these research directions advance, the construction sector can make more informed and impactful decisions, playing a significant role in achieving low-carbon and more resource-efficient built environments.

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