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AI-Driven Production in Modular Architecture: An Examination of Design Process and Method

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ABSTRACT

This study explores the incorporation of AI-driven production technologies within modular architecture, with an emphasis on optimizing design processes and facilitating practical application. By leveraging text-to-image technology via the Runway AI and Copilot AI platforms, a range of geometric moduls -including rhombic dodecahedra, cubes, hexagonal prisms, truncated octahedra, and triangular prisms-were utilized as prompts to generate architectural designs. The generated designs were subsequently assessed against established modular architecture criteria, with particular attention given to their structural integrity and construction feasibility. The AI-generated outputs exhibited notable versatility, yielding designs that met both structural and architectural standards. This methodological approach presents a new set of tools for architects, enabling them to explore intricate geometric forms while enhancing the efficiency of conceptual and design stages. The results indicate that the integration of AI-driven techniques into modular architecture has considerable potential to drive innovation, offering a more streamlined process for achieving creative and functional design outcomes. Moreover, the application of AI in this context not only expedites the generation of forms but also expands architects' capabilities in producing a wider array of high-quality architectural solutions.

1. Introduction

The architectural discipline has historically been defined by the intricate relationship between form, function, and aesthetics. Recent advancements in digital media, alongside emerging trends in contemporary architectural movements, have significantly expanded the architectural lexicon. These developments have introduced strategies for space configuration that prioritize both rapid implementation and adaptability. The integration of novel design tools, coupled with the evolution of digital construction techniques, has played a crucial role in enhancing the flexibility and transformability of architectural structures [1].

In recent years, advancements in artificial intelligence (AI) have significantly reshaped the architectural field, particularly with the integration of AI-driven production technologies. Among the most impactful AI applications in architecture is text-to-image technology, which allows the creation of intricate geometric forms based solely on textual input. This innovation presents exceptional opportunities for advancing modular architecture, a design approach that focuses on prefabricated,

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standardized elements capable of being assembled in a wide variety of configurations.

A modular architectural design approach offers an effective means of addressing these objectives by merging the benefits of flexibility with standardization [2]. Traditionally, modular construction has been related to the geometry and spatial arrangement of components, and more recently, it has been increasingly associated with advancements in the construction industry [3].

Modular architecture, characterized by its emphasis on efficiency, adaptability, and scalability, stands to gain considerably from AI-driven approaches that enhance both design processes and outcomes. Through the application of text-to-image technologies, architects can investigate a wider range of design possibilities and swiftly produce intricate geometric forms that would be laborious and complex to achieve through conventional methods. This paper explores the transformative impact of AI-driven production on modular architecture, focusing on platforms like Runway AI and Copilot AI. It examines the implications of these technologies for design methodologies, decision-making processes, and the autonomy of architectural systems, underscoring their potential to foster innovative solutions and streamline architectural workflows.

2. Literature Review

Modular structures, including temporary buildings, art installations, and urban furniture, have gained widespread application in the architectural domain [4]. These systems are composed of unit components that share identical or similar forms. By varying the arrangement of a certain number of these unit components, diverse patterns can be produced. This approach allows for flexible adaptation to a range of site constraints by either increasing or decreasing the number of units or altering their placement [4].

In numerous case studies examining modular architectural design across various scales, it has been consistently observed that the core of these studies revolves around the arrangement of modular components to produce solutions that align with the designer's intent. Throughout these processes, designers concentrate on the form and placement of components to achieve specific design objectives while addressing spatial limitations [5]. This reflects a typical reasoning process focused on the structure itself [6], where the designer's thought process and actions continuously shape and refine the modular construction.

In architectural design processes, freehand sketches [7] and the manipulation of objects within 3D modeling software represent fundamental methodologies for conceptualizing modular structures. This process of visual reasoning facilitates the ongoing translation of the designer's internal cognitive frameworks and intentions into external manifestations, such as sketches and three-dimensional models [8, 9]. These externalized forms provide a tangible medium through which designers can investigate, refine, and articulate their conceptual ideas throughout the design continuum. The use of these visual tools not only aids in the detailed exploration of design possibilities but also serves as a crucial mechanism for communication and collaboration among design stakeholders. By externalizing cognitive processes, designers can effectively share their vision and iteratively refine their concepts, thereby enhancing the overall coherence and efficacy of the design process. This iterative and communicative approach underscores the importance of visual representation in bridging the gap between abstract ideas and practical implementations in architectural design.

Nonetheless, it has been observed that designers often devote considerable time and energy to repetitive tasks within the design reasoning process [10]. For example, frequent repositioning of unit components may be required to reconfigure spatial relationships. Despite significant advancements in digital drawing and modeling tools, which have markedly enhanced design productivity and creativity over recent decades, these inefficiencies persist. Such repetitive activities continue to pose challenges, hindering the potential for more streamlined and efficient workflows even within advanced digital design environments [4]. These persistent inefficiencies underscore the need for innovative solutions that can further optimize and automate design processes, ultimately improving overall design efficacy.

In the age of artificial intelligence (AI), a pivotal inquiry emerges: can machines assist designers in enhancing design reasoning? Modular structure design, akin to other creative fields, is characterized by a distinctive, non-linear process that is intricately linked to the designer's logical reasoning and intuition [11]. The intuitive component, influenced by personal experiences and cognitive patterns that are often difficult to articulate, is considered a unique attribute of human designers [12]. This raises a fundamental question about the potential for machines to replicate or simulate the nuanced, intuitive decision-making that is central to the creative process [4]. This question also highlights the exciting potential of integrating artificial intelligence into creative fields, where the nuances of human intuition and subjective judgment play a significant role. AI offers valuable opportunities to introduce innovation and accelerate various stages of the design process. Looking ahead, exploring how AI can be effectively used as a tool to complement and support human creativity will be key to maximizing its contributions to creative processes.

3. Methodology

The methodology of this study encompasses three key steps: first, establishing the criteria for modular architecture and selecting the modules to be used as samples; second, conducting the AI-driven production phase; and third, evaluating the performance of AI-generated outputs within the context of modular architecture.

3.1 Modular Architecture Approach

The incorporation of computational techniques into architecture has afforded practitioners the chance to depart from conventional design and construction practices [3]. Modern building modules are arranged in various configurations—such as sequentially, side by side, or stacked—and are interconnected through methods including screwing and welding [13]. Modular construction allows for the addition or removal of units from the structure based on the needs of the users [14].

In the study, the initial objective is to assess whether artificial intelligence can effectively recognize geometric forms. Subsequently, the produced outputs will be evaluated in terms of their structural and constructional attributes. The evaluation criteria, which are chosen based on the modular architectural approach, have been reviewed in the literature as follows:

i. Flexibility: New modules can be added or removed from the design as needed [14].
ii. Similar Elements: The primary advantages of modular construction include a reduction in complexity, the use of standardized elements, the ability to create variety, improved independent problem-solving, and the facilitation of parallel workflows [15].
iii. Fabricate-to-fit modularity: A property of an element can be permanently changed through a non-reversible process that alters its physical dimensions [3].
iv. Volumetric units: Modules are preassembled as self-contained three-dimensional units, which are subsequently transported to the construction site and assembled. Each unit

may be comprised of smaller sub-modules and, depending on its dimensions, functions as a distinct element within the larger structure [16].

The choice of modules to be used in this study is as follows since there are five types of convex polyhedra with regular faces that tessellate the space: the triangular prism, the hexagonal prism [17], the cube, the truncated octahedron [18], and the triangular prisms (Fig. 1.) [3].

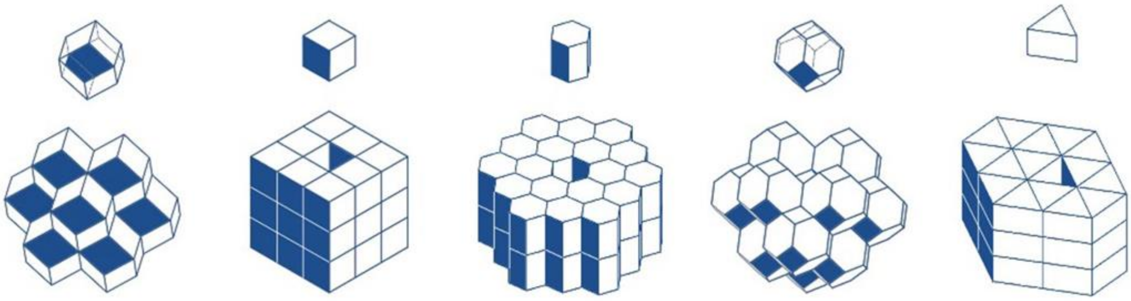


Fig. 1. Tessellations with rhombic dodecahedra, cubes, hexagonal prisms, truncated octahedra, triangular prisms [3].

3.2 AI-Driven Production

Machine Learning, a specialized branch of Artificial Intelligence, has recently ascended to prominence within the art and design sectors, establishing itself as a multifaceted tool, medium, and platform for practitioners [19]. Among the notable advancements in this field are diffusion models, which have been trained on extensive datasets to generate a diverse array of designs in response to textual prompts [20,21]. Traditional diffusion models are defined by two fundamental stages: the forward process and the reverse process. In the forward process, controlled noise is incrementally introduced to the initial image, leading to a progressively deteriorated version. Conversely, the reverse process endeavors to reconstruct the original image from this altered version [22]. By mastering the denoising technique, diffusion models gain the capability to generate novel images [23]. When designers seek images that incorporate specific design attributes, they can input text prompts during the denoising phase of the diffusion model, thus producing images that are both consistent and manageable [21,24]. The primary advantage of text-guided diffusion models in image generation is their capacity to offer precise control over the resulting images [20,21,25]. Machine Learning, particularly through diffusion models, represents a transformative advancement in art and design by enhancing the precision and flexibility of creative processes. These models significantly streamline the generation of complex visual content, allowing designers to produce highly specific and controlled results from textual descriptions. This technological innovation not only facilitates more intuitive and efficient design practices but also broadens the scope of creative possibilities. The ability to integrate text prompts into the diffusion process highlights a pivotal shift towards more adaptive and versatile design tools, marking a notable evolution in how creative concepts are conceived and executed.

In recent years, diffusion models have swiftly become predominant in the field of image generation [21, 26, 27], offering designers the capability to obtain images rapidly and thereby significantly enhancing architectural design efficiency and quality [21, 23]. The accelerated advancements in artificial intelligence and technology indicate that, in the future, AI could evolve into an algorithm capable of learning the process of “designing” through emerging hardware and algorithms. Consequently, the field of architecture is expected to evolve and transform in tandem with technological progress [28].

In this study, Runway AI and Copilot AI, advanced artificial intelligence interfaces utilizing machine learning technology, was employed. Runway AI is a sophisticated platform designed to enhance the application of artificial intelligence across creative and design disciplines. It provides a comprehensive array of AI models and tools tailored to various multimedia and artistic needs, including text-to-image generation, video editing, and sound processing. A key feature of the platform is its text-to-image capability, which allows users to produce intricate visual content from textual descriptions. Through the use of advanced machine learning algorithms, Runway AI converts textual prompts into detailed and contextually relevant images, thereby broadening the creative potential for designers and artists [29]. Microsoft Copilot AI is an advanced AI-powered tool integrated into various Microsoft applications to assist users in generating content, automating tasks, and enhancing productivity through natural language processing. It leverages large language models to understand and respond to prompts, making it highly effective in tasks like document drafting, data analysis, and content creation, including text-to-image generation in specific cases [30].

The sample modules selected for the study were input into the Runway AI and Copilot AI bots using the following prompts to facilitate both structural and constructive production:

“Modular architectural structure consisting of Tessellations with rhombic dodecahedra
Modular architectural construction consisting of Tessellations with rhombic dodecahedra

Modular architectural structure consisting of cubes
Modular architectural construction consisting of cubes

Modular architectural structure consisting of hexagonal prisms
Modular architectural construction consisting of hexagonal prisms

Modular architectural structure consisting of truncated octahedra
Modular architectural construction consisting of truncated octahedra

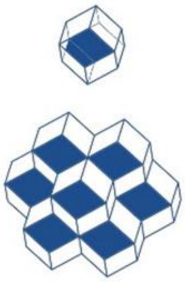
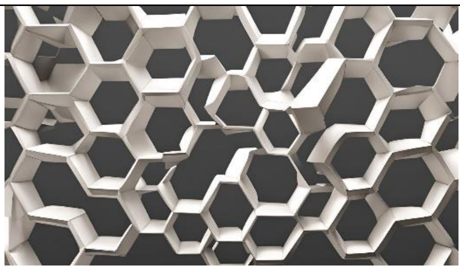
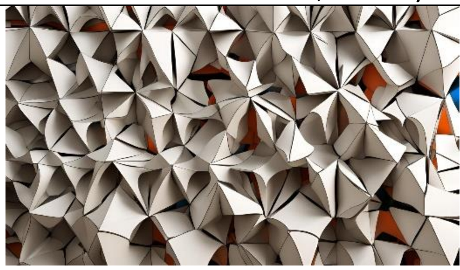
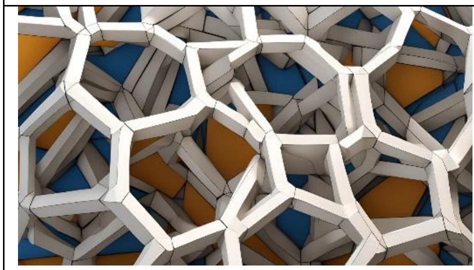
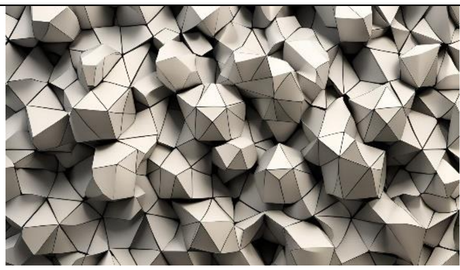
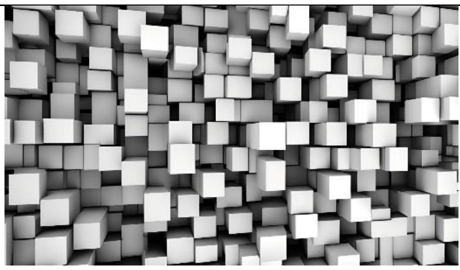
Modular architectural structure consisting of triangular prisms
Modular architectural construction consisting of triangular prisms”

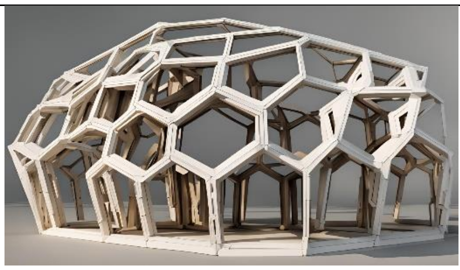
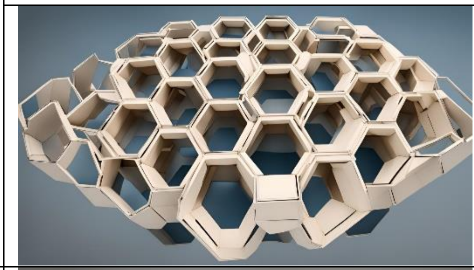
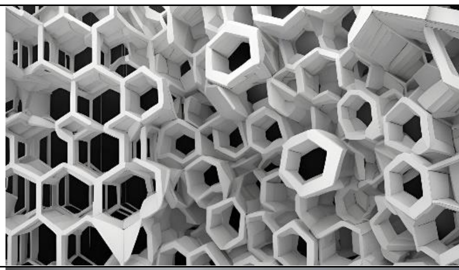
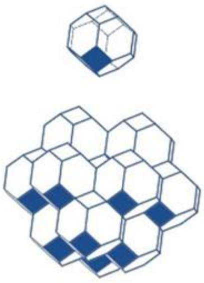
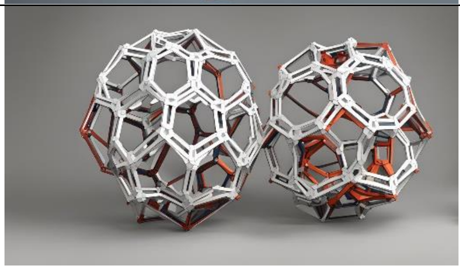
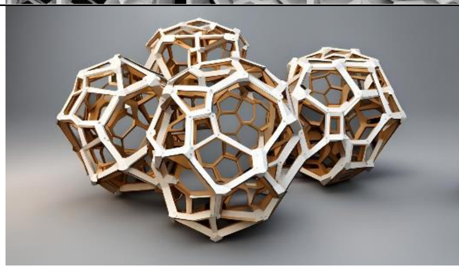
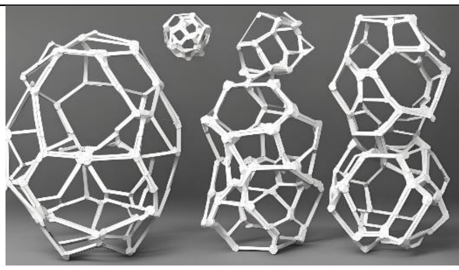
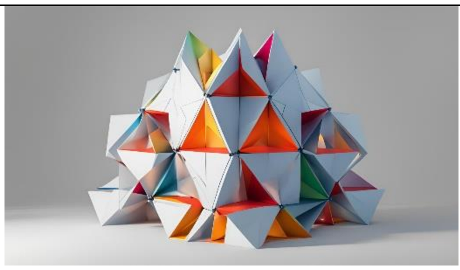
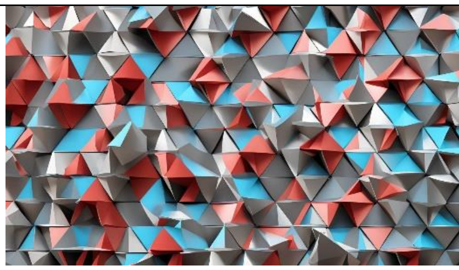
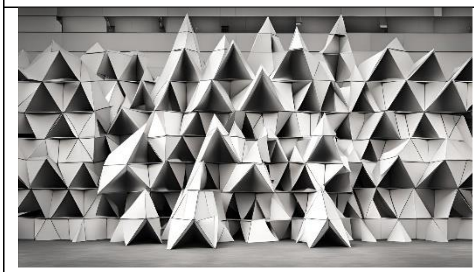
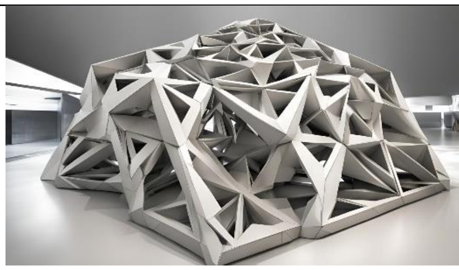
4. Results and Discussion

The evaluation phase of the results was conducted through reciprocal discussions among a group of architects specializing in architectural design. The experiences with two separate AI bots were initially deliberated within their respective contexts. In the evaluation of AI within the context of modular architectural production, one of the fundamental motivations of the study is to question whether the AI bots serve as a design tool or as a design parameter by comparing the outputs generated by different bots.

The results obtained from entering prompts into the Runway AI artificial intelligence interface were initially evaluated based on the structural prompt, as detailed in Table 1. Upon analysis, it was observed that despite the prompts only specifying the terms "modular architectural structure" and the names of geometric forms, without any additional criteria, the AI-generated visual results were deemed successful. Among these results, the least successful outcomes were those generated for structures composed of cube modules, which were observed to be merely graphical representations rather than functional architectural solutions. Modular structures composed of triangular prisms and truncated octahedra, while qualitatively better, did not achieve the highest level of success. The most successful results were obtained when the prompt specified hexagonal prisms. These outcomes were found to be inspiring for architects. The AI's ability to recognize complex geometries and generate results without predefined criteria suggests that further development of this pilot study could enhance the significance of AI in architecture. The autonomous, rapid, and highly varied nature of the results not only expands possibilities but also redefines the architect's role in selecting from numerous alternatives.

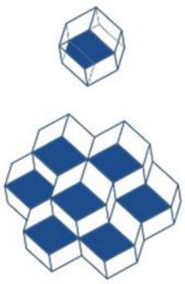
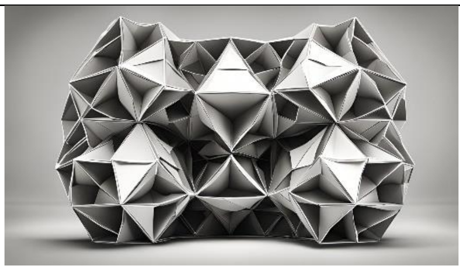
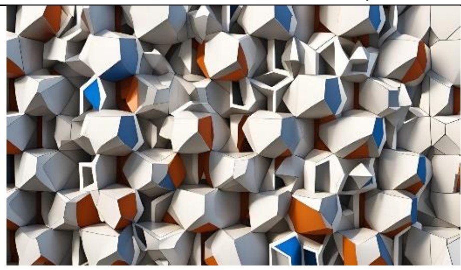
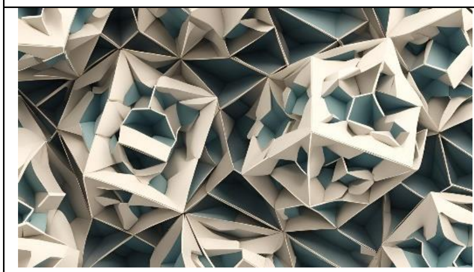
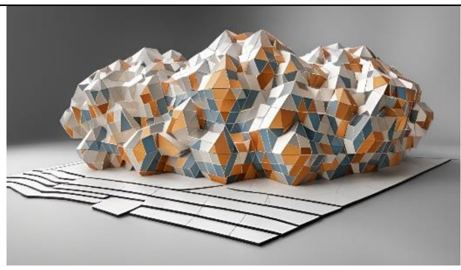
Table 1
AI-Driven Production in Modular Architecture in a structural context, Runway AI

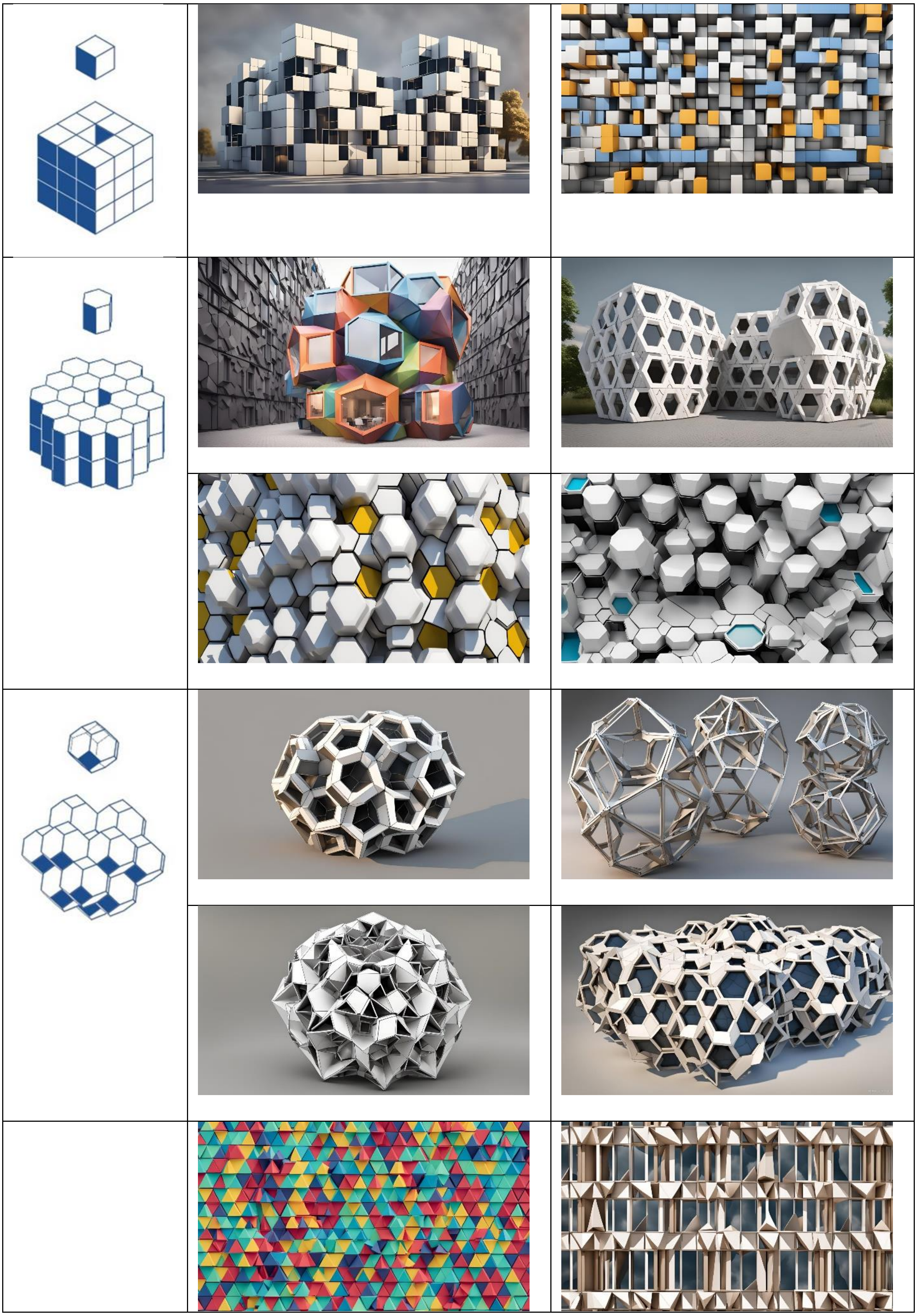
		
		
		
		

In the second phase for Runway AI's production of the study, the same prompts were entered into the Runway AI bot, this time with a focus on "constructional" aspects. No additional criteria were specified, such as color, material, aesthetic evaluations, balance, or rhythm. Despite the absence of these descriptors, the results, as presented in Table 2, reveal that the AI incorporated architectural materials and color, aspects not considered in the structural phase. Furthermore, there is evidence of aesthetic elements such as repetition, rhythm, and balance, which is noteworthy. In this phase, the least successful outcomes were those derived from truncated octahedra, with results remaining largely at a structural level. Conversely, the visual construction products generated from cubes, initially evaluated as the least successful in the structural phase, were deemed successful in this phase. These cube results offered façade-like products, whereas the visual products, regarded as complete constructions, were assessed as successful architectural structures using a modular approach characterized by the relationship between solid and void. The initial visual from hexagonal prisms demonstrated successful use of color in architecture. The most successful architectural product in this phase was the third result obtained from the triangular prisms prompt, which not only adhered to design principles but also effectively utilized glass as an architectural element, showcasing the AI's capability to deliver a successful outcome. In this context, it is anticipated that providing the AI with additional criteria (such as color, material, and dimensions) could yield more customized and desired architectural visual outputs. This would further strengthen the architect's role in decision-making.

Table 2
AI-Driven Production in Modular Architecture in a constructional context, Runway AI

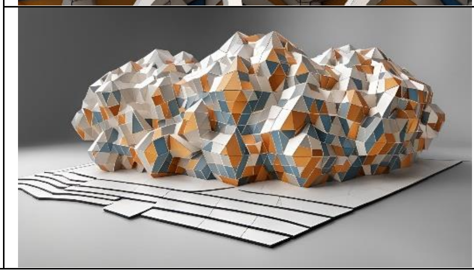
		
		
		

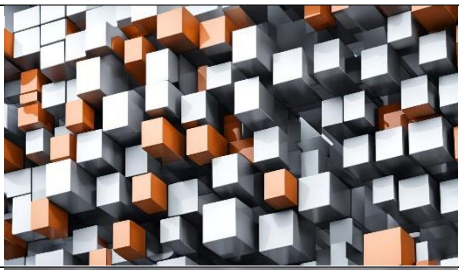
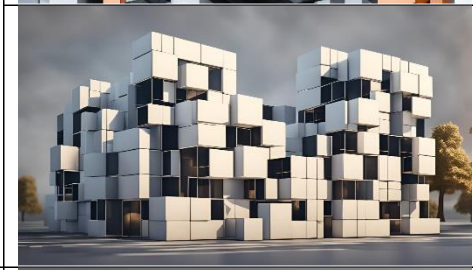
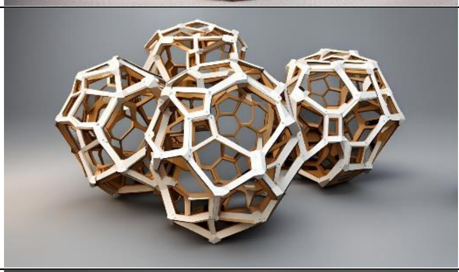
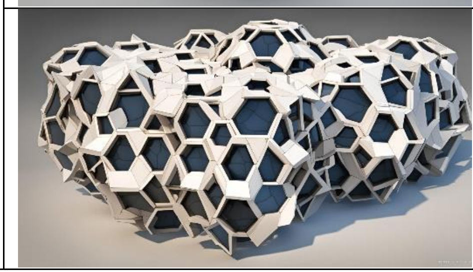


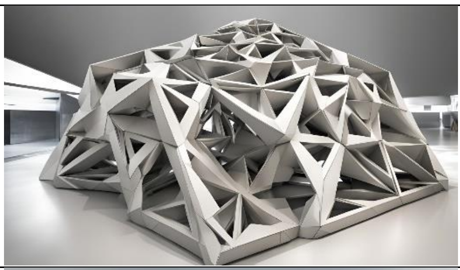
		
		

The final evaluation for Runway AI's production was conducted based on the criteria established through the literature review within the study. For this assessment, the most successful results for both structural and constructional aspects of each geometry were selected. The evaluation is detailed in Table 3.

Table 3
Evaluation in the context of modular architecture approach for Runway AI's production

		Flexibility	Similar Elements	Fabricate-to-fit modularity	Volumetric units
Tessellations with rhombic dodecahedra			**X**		
		**X**	**X**	**X**	**X**

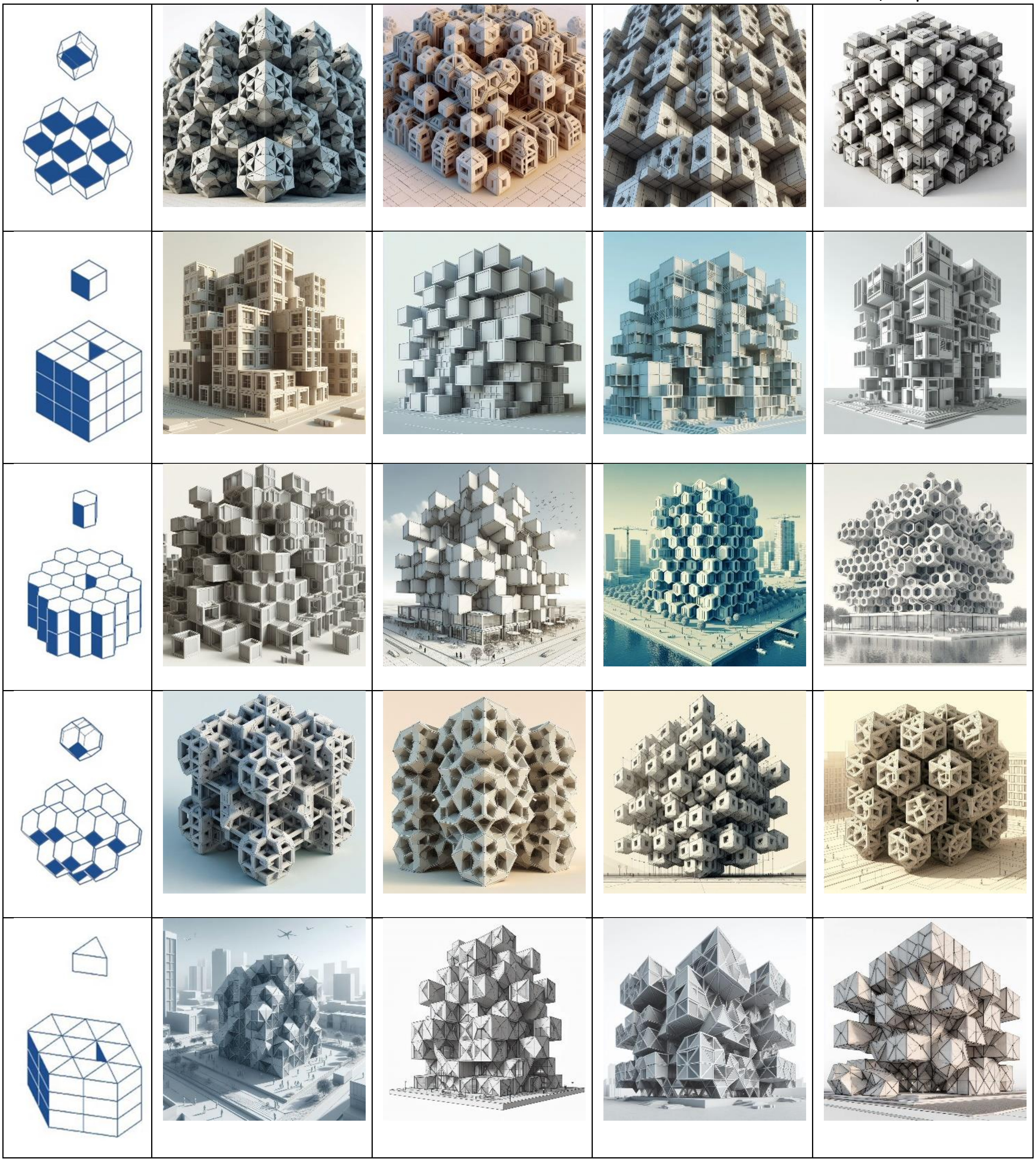
Cubes		X	X	X	X
		X	X	X	X
Hexagonal prisms		X	X		
			X	X	X
Truncated octahedra			X	X	X
		X	X	X	X

Triangular prisms			X		
		X	X	X	X

When evaluating Runway AI-driven production in modular architecture, it can generally be stated that the results were found to be successful. The AI interface used in this study, Runway AI, demonstrated the capability to recognize geometry, conduct structural and constructional evaluations, and produce designs aligned with modular architectural approaches. However, incorporating more detailed descriptors in the prompts could yield results that are more focused on the desired outcomes. Despite this, all the outputs remain visual representations. Since the discipline of architecture extends far beyond visual outputs, architects will always maintain their role as decisive authorities.

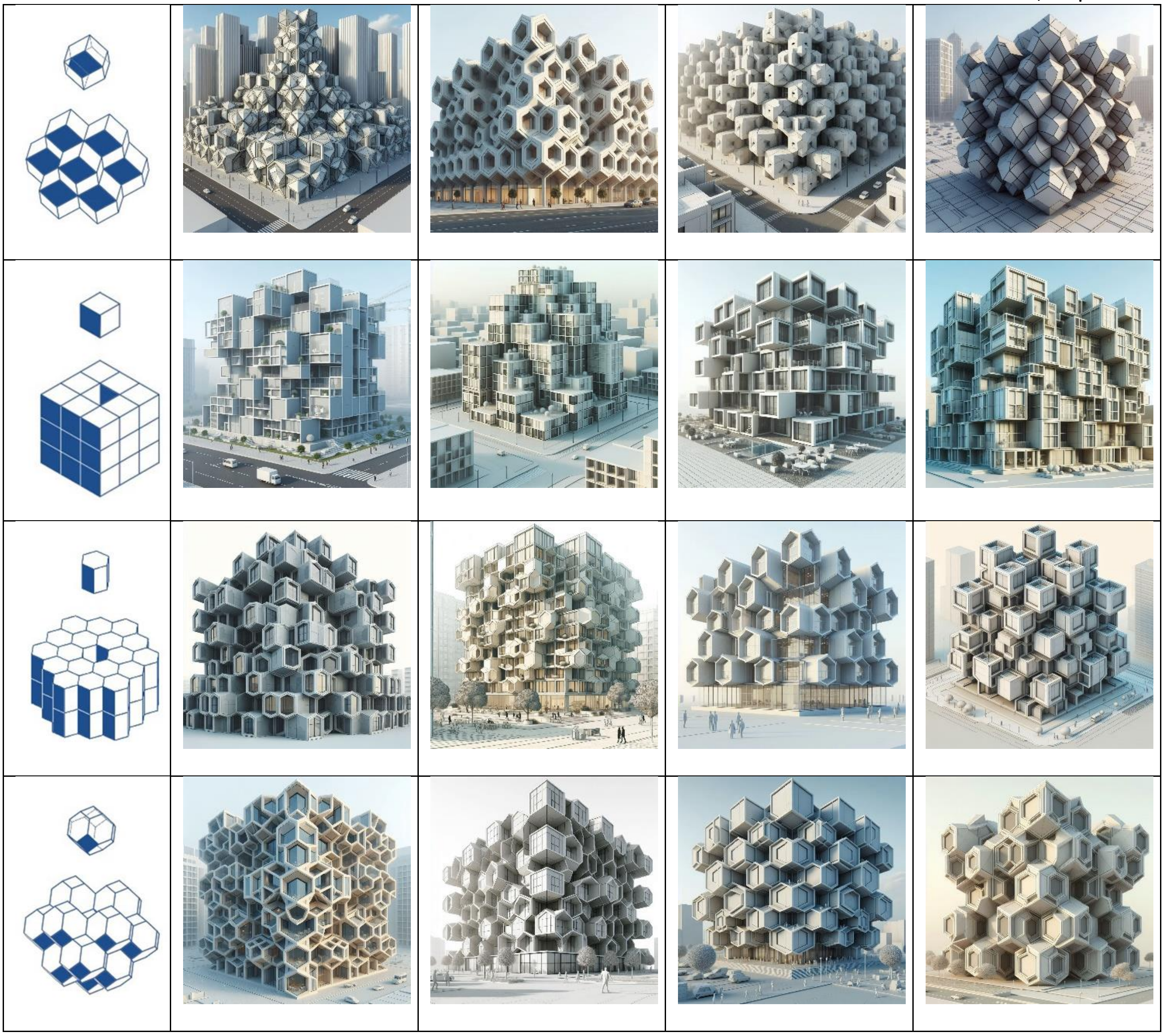
The same production process was replicated using a different AI tool, Copilot AI (Table 4). The purpose of this repetition is to delineate the relationship between the success or failure of the architectural products generated and the AI tools employed. It can be stated that the initial phase of structural production, where only "modular architectural structure" and the names of geometric forms were input as prompts, yielded generally successful results. Among these outcomes, the most surprising finding was that while Runway AI produced the least successful output for a structure composed of cubes, Copilot AI achieved highly successful results for the same request. These productions were evaluated not only for their mathematical modular repetition and flexibility regarding the cube but also for their applicability as architectural structures rather than merely graphical visuals. An interesting aspect of the Copilot AI production experience is that it utilized cubes in the structural design of each geometric form. When discussing the modular structure prompt results with tessellations involving rhombic dodecahedra, hexagonal prisms, truncated octahedra, or triangular prisms, both the desired geometries and cubic geometries were successfully produced in all instances. This phenomenon is believed to stem from the AI's use of cubes as intermediate elements in producing architectural structures, enhancing realism and applicability in functional design contexts. However, the architectural modular structures generated with tessellations of rhombic dodecahedra, which were evaluated as the least successful results, featured cubes as the primary units, with the geometric forms serving merely as decorative elements or façade components.

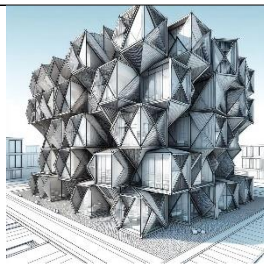
Table 4
AI-Driven Production in Modular Architecture in a structural context, Copilot AI



Without entering additional criteria such as color, material, aesthetic evaluations, balance, or rhythm, and only specifying geometry -with the term "architectural construction" given as a prompt to Copilot AI- no significant difference was observed compared to the results from Runway AI. While a clear distinction in architectural visuals was noted in the structural and construction outputs of Runway AI, the styles of Copilot AI outputs (Table 5) appeared to be the same. The architectural identity of the structures was preserved in the structural results, and visual products were obtained in the same style for the construction prompts. Parallel to the structural results, the most successful output products were again considered to be modular architectural structures composed of cubes. The designs, which maintain balance through the relationship between solid and void, were also found to be applicable. Similarly, consistent with the structural results, cubes were also present in the outputs of other geometric forms. Overall, the resulting designs were observed to possess aesthetic qualities while also being practical architectural designs. The successful element of "color" found in the Runway AI outputs was not achieved in the Copilot AI productions. Results obtained when additional descriptive characteristics are entered into these prompts according to text-to-image technology will also be detailed. However, the fundamental inquiry of this study is to test whether results can be achieved solely by specifying the names of complex geometries without any preliminary engineering or mathematical preparation, using basic information prompts.

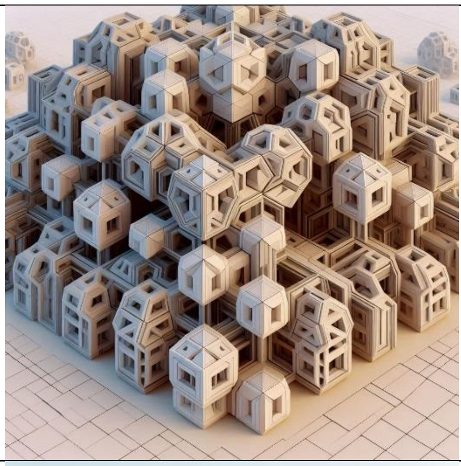
Table 5
AI-Driven Production in Modular Architecture in a constructional context, Copilot AI



The final evaluation for the production using the second AI tool, Copilot AI, was conducted based on the criteria established through the literature review within the study, following discussions among experts. For this assessment, the most successful results for both structural and constructional aspects of each geometry were selected. The evaluation is defined in Table 6.

Table 6
Evaluation in the context of modular architecture approach for Copilot AI's production

		Flexibility	Similar Elements	Fabricate-to-fit modularity	Volumetric units
Tessellations with rhombic dodecahedra		X		X	X
		X	X	X	X

Cubes		X	X	X	X
		X	X	X	X
Hexagonal prisms		X	X	X	X

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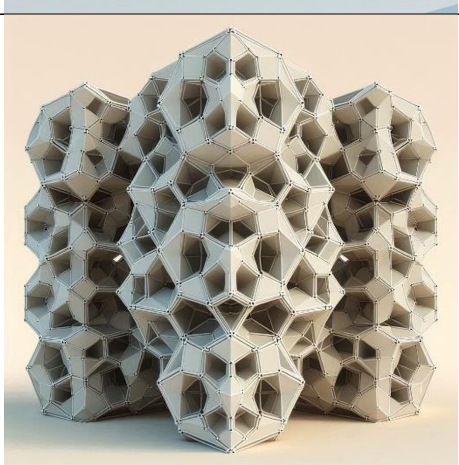
		**X**			**X**
Truncated octahedra					**X**
					**X**

Triangular prisms		X		X	X
		X	X	X	X

In this study, which involved the experience of both AI tools, it was revealed that different AI bots yield varying qualities and styles of results, highlighting the necessity of evaluating these bots as design parameters. The increasing number of text-to-image AI bots is generating inspiring outcomes in architectural design, prompting inquiries into the decision-making mechanisms. This study demonstrates the integration of the modular architectural design approach alongside this evolving technology and proposes a method and process for architectural design.

The autonomy, rapidity, variety, and text-based nature of the results represent a revolutionary advancement for the field of architecture.

5. Conclusions

In conclusion, the integration of AI-driven production technologies into modular architecture has introduced significant innovations and efficiency improvements in architectural practice. This study utilized text-to-image technology through the Runway AI platform, which enabled the generation of various geometric forms based on text-based descriptions and prompts. Text-to-image technology employs AI algorithms to automatically create visual content based on textual descriptions, allowing designers to rapidly and effectively produce forms with specific geometric attributes, thus surpassing traditional design methods.

The findings of this research demonstrate that the alternatives generated by AI are in compliance with modular architecture criteria in both structural and constructional aspects. Text-to-image technology not only provides aesthetically and functionally satisfactory solutions but also accelerates the design process and enhances efficiency. The designs produced by AI offer innovative and practical solutions, facilitating the development of modular architectural systems with a broader range of design diversity.

The capacity of AI systems to learn and process complex geometries represents a revolutionary advancement and significant convenience in the field of architecture. These technologies enable the rapid and accurate production of complex geometric forms, making these processes more accessible and surpassing traditional design methods. The automated processing of complex geometries fosters the creation of more innovative and aesthetically pleasing architectural solutions, marking significant advancements in both creative and technical aspects of the design process. Moreover, the role of AI-driven production processes in decision-making and their potential for autonomy is a crucial finding. The ability of AI systems to make automated decisions during the design phases accelerates the design process and reduces dependency on human intervention. This facilitates a more predictable design process and allows designers to focus on more strategic and creative tasks. AI supports decision-making processes by offering optimal solutions based on specific design parameters and contributes to the effective role of autonomous systems in the design process.

In this context, the application of AI technologies in modular architecture promotes both creative and functional innovations in the design process. Future research may explore how text-to-image technologies and AI systems can be integrated into larger-scale projects and diverse architectural approaches, further elucidating the role of AI in architectural practice. Such studies will contribute to a deeper understanding of the innovations and efficiency gains brought by AI-driven tools in architectural design processes.

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