

Exploring the Intersection of Biological and Artificial Neural Networks in Architectural Contexts, Followed by Investigation of Algorithms Supporting the Evolution of the Design Process

Raghad N Jasim ^{1*}, Anwar S. Al-Qaraghuli ², and Zuhair A Nasar³

1 University of Technology, Baghdad, Iraq

2 University of Technology, Baghdad, Iraq

3 University of Kufa, Najaf, Iraq

Abstract. This review explores the relationship between neural networks and architecture, specifically in the domains of facade design, interior design, and building construction. It investigates two types of neural networks: biological, representing the human brain's neural system, and artificial, which are computational systems inspired by the brain's structure and functions. The study provides a descriptive overview of these neural networks and their applications across various fields. It further examines how these networks integrate with architecture at different levels. The study emphasizes the concept of "neural architecture," which combines artificial neural networks (ANNs) with architecture to generate multiple design possibilities and uncover hidden patterns. ANNs are utilized in creating smart buildings and optimizing structural design processes to reduce costs. Additionally, the study explores "neuroarchitecture," which explores the interaction of biological neural networks (BNNs) with architecture, focusing on the impact of built environments on the brain and behavior. It combines principles from neuroscience, architecture, and environmental psychology. The analysis of case studies demonstrates the importance of AI tools such as 'pix2pix', GCNNs, DCGAN, CycleGAN, and StyleGAN in modernizing architectural design by blending traditional and contemporary styles and enhancing the creative process.

1 Introduction

The integration of artificial intelligence (AI) into art reached a significant milestone in 2015 with the development of the Generative Adversarial Network (GAN) and research on the "Neuro-Algorithm of Artistic Style." This breakthrough led to the emergence of "Nervous Art," a new artistic expression embraced in art and music. Artists like Mario Klingemann and Sofia Crespo pioneered this genre, utilizing algorithms to create unique themes. Crespo's "Nervous Zoo" series, focusing on deep-sea creatures, exemplifies the use of neuroscience techniques to generate both familiar and exotic images. Klingemann, on the other hand, employs StyleGAN to create distorted yet recognizable artworks. Nervous Art is an evolving genre, with contributions from various artists continuously shaping its growth [1]. Artificial neural networks (ANNs) and cognition have broad applications, including in philosophy and cognitive processes. Although deep learning is successful in simpler tasks, the complexity of "thinking" poses a challenge. The

*Corresponding Author: raghadnsaif95@gmail.com

utilization of synthetic neural networks helps bridge the gap between correlative and symbolic logic, advancing the interpretation of symbolic thinking [2].

ANNs, inspired by the human brain, are computational systems with neuron-like structures for signal transmission and information processing. They consist of interconnected nodes arranged in layers and excel at multitasking and solving complex problems in diverse fields [3]. ANNs consist of interconnected neurons that learn through adjustable weights, forming input-output relationships. They acquire patterns from data instead of explicit programming, enabling task-specific performance based on the received data [4]. On the other hands, Neuroscience explores the nervous system, which includes nerve cells processing information for bodily responses. It investigates the intricate communication pathways of the brain, controlling muscles and organs, and forming sensory-based representations of the external world [5]. The nervous system, histologically, comprises nerve and glial cells. Nerve cells receive and transmit electrical impulses, influencing other cells throughout various regions [6]. The human nervous system consists of specialized neural networks that coordinate functions such as vision, hearing, and emotion, enabling complex bodily activities [7]. These networks, known as Biological Neural Networks (BNNs), embody the interconnected complexity of the nervous system [8].

The advancements in technology and machine learning have enabled the extensive application of ANNs in improving diagnostic accuracy and efficiency. ANNs are utilized in various domains, including decision-making, pattern recognition, and facial detection. In medicine, they assist in diagnosing conditions like shortness of breath, support therapeutic applications for cancers, and predict patient outcomes in treatments such as radiotherapy for esophageal and non-melanoma skin cancers [9].

ANNs have brought about a revolution in the chemical industry by enabling the stimulation of chemical reactions through the use of auxiliary factors. This approach has resulted in enhanced resource utilization, reduced pollution and waste, and enhanced safety in chemical processes [10].

The collaboration of ANNs with human learning in architecture and design emphasizes the importance of unsupervised learning frameworks. This convergence of computer science, neuroscience, and architecture, particularly in Generative Design Research, drives innovation in creating adaptable architectural solutions [11]. The construction sector, responsible for a significant amount of global data, is increasingly utilizing ANNs for efficient data processing, particularly in handling large datasets. Future advancements should focus on streamlining data collection and processing, standardizing data, and integrating automated systems for improved management efficiency [12]. Adopting a holistic approach in project life cycle management is crucial for reducing total cost of ownership [13]. Additionally, the relationship between architectural design, human cognition, and subjective experience is explored and evaluated using neuroscience tools [14].

Computer vision (CV) focuses on developing algorithms that enable computers to process and interpret visual data, akin to human vision. It incorporates body detection, scene reconstruction, and extensively utilizes ANNs [15]. Neuroscience aids in understanding human vision, assisting computer science in creating machine learning algorithms for CV. While cameras detect elements like infrared light, computer vision faces challenges in context interpretation compared to humans. In practical terms, CV helps robots navigate and map environments, employing stereo cameras for distance calculation and 3D modeling [16]. This research explores the complex integration of various scientific fields, particularly the neural concept, and its impact on diverse areas such as medicine, chemistry, physics, and architecture. The study aims to provide a comprehensive understanding of how this knowledge influences architectural engineering. It introduces both biological and artificial neural networks and their intersection with architecture. The research focuses on the design aspect, analyzing case studies to offer insights relevant to architectural designers. It aims to provide a clear understanding of the tools and methods that facilitate the adoption of neural architecture as a promising design approach, along with concluding remarks and recommendations.

2 Levels Of the Neural Concept in Architectural

The neural concept and architecture intersect on various levels. Neural networks generate unique creative outputs based on computer vision techniques. Neural networks also play a significant role in gathering information from buildings, aiding decision-making processes in architecture. Furthermore, the neural concept influences architectural behavior, where the interaction between neurons and behavior is crucial. Technologies like virtual reality and augmented reality enhance this interaction in architectural design.

2.1 Design Process Level

Integrating machine-learning techniques into architectural design processes enhances data-rich environments, leading to innovative practices. Machine learning in generative design combines parametric models with generative processes, enabling exploration of various design possibilities. By breaking the link between performance metrics and design assessment, architects achieve more flexible and diverse design outputs. Machine learning integration with simulation uncovers insights from large and diverse datasets, benefiting from building information models across disciplines. However, understanding this information requires explicit knowledge declaration and synthesizing multiple models. Machine-learning helps architects analyze vast amounts of data, identify patterns or anomalies, and make informed decisions. Effective machine-learning implementation in architecture relies on methods to query and classify information in different representations [11].

Neural architecture is the architectural aspect that primarily explores the inherent field of ANNs as a design methodology [1].

The potential of machine-learning in complex and unknown design problems lies in its ability to handle uncertainties without defined parameters. Machine-learning algorithms can be applied at various design stages and scales. However, customization is crucial for effectiveness, with tailored solutions instead of generic ones. Integrating Machine-learning into design practices raises resource and effort concerns. To address this, the design profession should focus on transferring and sharing foundational datasets and trained algorithms, fostering collaboration and knowledge exchange instead of relying on one-off solutions [11].

As shown in the figure 1; the design of the Austrian pavilion at Expo 2020 in Dubai departed from traditional 19th-century methods by employing neural networks based on historical data. The roof of the pavilion was created using the 2D Neural/style transfer method, incorporating datasets of baroque and modern ceilings. The resulting design language strikes a unique balance between the two styles, neither purely baroque nor entirely modern. By adjusting the weights of different layers in the neural networks, multiple design solutions can be generated. The final decision on which solution to use rests with the designer, who continues the design process. This example exclusively utilized Austrian baroque images and modern ceilings to capture a distinct Austrian spatial quality [1].



Fig. 1. Austrian pavilion of Expo 2020 in Dubai [1].

2.2 Building Construction and Operating Level

The construction industry's focus on efficient practices due to extensive resource and energy use is driving research in predictive models. ANNs are being developed to assess the impact of communication factors on rework costs in construction projects [17]. Some studies propose a unified approach, combining trained ANNs into a Unified Function (UFO), for optimizing multiple objectives simultaneously. This optimization process is valuable in designing structural systems and provides guidance for engineers and decision-makers in the initial design phase [18].

Resilient design using ANNs outperforms human-driven processes in optimizing Reinforced Concrete (RC) frames. By substituting complex analytical objective functions with ANNs-based functions, this approach enhances design accuracy for beams, columns, and frames. These autonomous artificial neural genes optimize design targets considering cost, weight, and adherence to design codes, representing a significant advancement in structural analysis and design research. This shift towards AI-driven optimization marks a new era in Data-centric Engineering, surpassing traditional structural mechanics [19].

ANNs are integrated into architectural buildings to achieve smart construction goals, improving energy efficiency, comfort, and user satisfaction. Advanced sensors and software monitor internal and external conditions, enabling better control of comfort and security systems for optimized energy consumption. A data-driven model using ANNs accurately forecasts internal temperature, contributing to further energy optimization. The model's effectiveness was validated using data from an existing building [20].

ANNs have shown great effectiveness in construction and power system upgrades, providing optimal retrofit solutions. In Zurich, Switzerland, an ANNs model reduced computational costs while maintaining accuracy in retrofitting scenarios. In southern Italy, ANNs were used to predict energy performance in non-residential building retrofits, considering emissions, costs, and multi-standard decision-making [21].

2.3 Behavior Level

Neuro architecture is an emerging field that investigates the subconscious neurophysiological interactions between architectural spaces and human experiences. By utilizing neuroscientific techniques to record neural activities, it provides insights into the connection between architecture and psychology. This field explores how different architectural patterns influence human perception and subjective experiences, shedding light on fundamental mental processes. Recent advancements in neuroscience enable a focused examination of human responses to architecture, addressing the limited objective evidence supporting this connection in the past. Architects and urban planners can benefit from the knowledge gained through neuroarchitecture to create more impactful and meaningful environments [22].

Neuroarchitecture, an interdisciplinary field combining neuroscience, architecture, and environmental psychology, explores how the built environment affects the human brain and informs building design for improved health and well-being. It considers how people interact with their surroundings and offers insights for future design strategies in different settings. Advances in brain imaging technology accelerate the field's growth, emphasizing embodied experiences and the interplay between the brain, body, and environment [23].

The field of neuroarchitecture initially focused on the connection between brain structure, function, and cognition, leading to a stronger link between architectural research and neuroscience. Advancements in technologies like EEG, fMRI, and virtual reality provided valuable insights for designers and psychologists [22]. Architectural ergonomics, informed by research, explored the interaction between environmental features and people's physical abilities. Innovations like MoBI captured brain activity during engagement with the built environment for improved design and well-being [23].

Designing based on neuroscientific principles is evolving, with efforts aimed at enhancing human cognitive-emotional responses in architectural environments. Adapting existing spaces and making informed decisions in designing new ones are key considerations. The combination of neuroscience and environmental simulation advancements has the potential to significantly impact this emerging discipline. Architects embracing these possibilities can shape the future of the field, presenting promising and exciting challenges [24].

3 Case Studies

This research aims to investigate the role of neural architecture in the design process by focusing on the definition of neural architecture, the architect's scope of work, and their tools for design development. However, due to the complexity and breadth of this topic, it may not cover all aspects of design process, building construction, and behavior. The study will provide insights into the contemporary reality of neural architecture in architecture.

3.1 Architectural Drawings Recognition and Generation through Machine Learning

Huang and Zheng [25] excelled in generating realistic images, particularly in the 'pix2pix' and 'Pix2pixHD' architectures. Generative Adversarial Networks are AI models comprising a generator and a discriminator. Their application in transforming and recognizing architectural drawings is noteworthy. GANs, especially 'pix2pix', are revolutionizing various fields by generating realistic images from damaged or monochrome inputs as shown in the figure 2. This study utilized Python and PyTorch to investigate the relationship between architectural drawings and color-coded maps. A dataset from lianjia.com, consisting

of consistent style and scale colored floor plans, was employed. The study involved 115 labeled image pairs and utilized Pix2pixHD to convert floor plans to maps and vice versa, enhancing architectural plan recognition and creation. The experiments with 'pix2pix' and 'Pix2pixHD' demonstrated their effectiveness in recognizing and generating detailed architectural plans, showcasing their value in digital architecture.

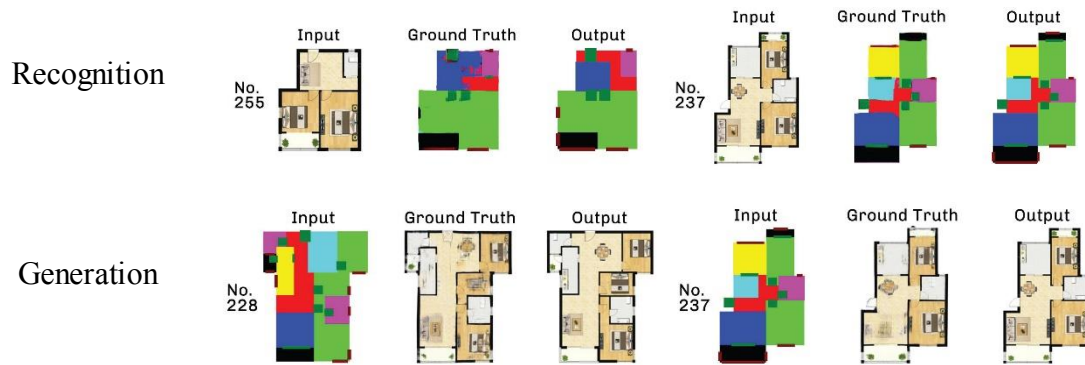


Fig. 2. Apartment floor plan: recognition and generation through generative adversarial network [25].

3.2 3D Graph Convolutional Neural Networks in Architecture Design

Del Campo et al. [26] investigated the application of 3D deep learning, specifically Graph Convolutional Neural Networks (GCNN), in architectural design. It explores the use of advanced AI algorithms to process and analyze three-dimensional architectural data, aiming to enhance creativity through 3D modeling. By integrating artificial intelligence, particularly 3D Neural Modeling, with architectural aesthetics and intuition, the study examines perception and awareness in design. A comprehensive database of architectural models was created, and a GCNN was trained to associate these models with aesthetic and intuitive features, with the goal of optimizing AI-enhanced design. Using models from TopMod and Autodesk Maya, an "intuition set" was developed and evaluated for function and aesthetics. The GCNN successfully classified diverse models into styles such as Baroque and Cubist, effectively linking 3D model features to style, aesthetics, and functionality as shown in the figure 3. This demonstrates the potential of GCNNs in recognizing and replicating complex architectural concepts.



Fig. 3. The Inputs Visual Representations of the Complete Sensibility Dataset and The Outputs Including Style, Functionality and Aesthetics [26].

3.3 Deep Learning as Heuristic Approach for Architectural Concept Generation

Bolojan et al. [27] investigated the impact of AI on creativity in architectural design, drawing inspiration from early developments in AI and computational creativity. Focusing on the creative aspect of architecture, the study references historical advancements in creativity research, including Margaret Boden's work, to explore AI's role in understanding human creativity. The study employs The Sagrada Familia as a complex case study for neural network analysis, aiming to translate human perceptions of symbolic architectural meanings into visual forms. The CycleGAN algorithm is utilized to explore translations between architectural styles in The Sagrada Familia as shown in the figure 4. CycleGAN is a type of GAN specifically designed for image-to-image translation tasks, enabling the conversion of images from one style or domain to another. The success of the translations is evaluated using a combination of objective metrics like SSIM and subjective assessments. The results demonstrate the capabilities and challenges of AI in interpreting and replicating architectural styles, emphasizing the importance of both automated and human evaluations in AI-generated designs.

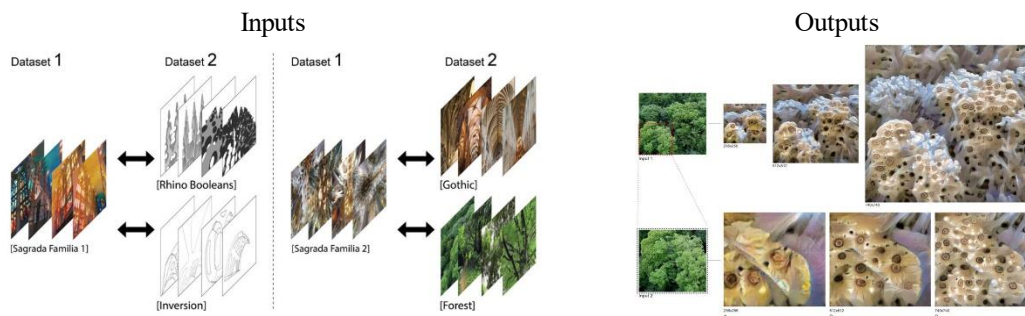


Fig. 4. The Input Using Two Distinct Datasets from the Sagrada Familia and The Outputs of training the CycleGAN Varied Based on Different Resolutions and Hyperparameters [27].

3.4 Deep Convolutional Generative Adversarial Network to Investigate the Virtual Design Space of Historical Islamic Patterns

Alani and Al-Kaseem [28] examined the impact of digital technologies, specifically Deep Convolutional Generative Adversarial Networks (DCGAN), on reshaping the design process in Islamic architecture. DCGAN is a variant of GAN that utilizes deep convolutional neural networks, improving its effectiveness in handling image data. By focusing on AI's role in architectural design, the study demonstrates how DCGAN learns from existing designs to innovate within the traditional constraints of Islamic architecture. The approach involves analyzing the internal structures of Islamic designs and using DCGAN to explore new shape possibilities while preserving the essence of traditional forms. Drawing on Gilles Deleuze's philosophy, the study utilizes DCGAN to capture and recreate the 'virtual design space' of Islamic geometric patterns, particularly those based on hexagons as shown in the figure 5. The results show that DCGAN successfully generates new designs that are both authentic to Islamic patterns and innovative, highlighting the potential of digital technologies in reinterpreting historical designs.



Fig. 5. Real Samples of Historical Data as The Inputs, and Random Noise as A Foundation to Develop Hexagon Shaped Geometric Patterns [28].

3.5 Architectural Form Explorations through Generative Adversarial Networks Predicting the potentials of StyleGAN

Eroğlu and Gül [29] investigated the application of StyleGAN, an advanced Generative Adversarial Network that leverages deep convolutional neural networks, in style transfer for neural networks. This approach effectively separates and combines image content and style, resulting in high-resolution rendering and improved image quality as shown in the figure 6. The study focused on StyleGAN's image generation capabilities in architectural design, utilizing various datasets. Specifically, they selected building images classified into three architectural styles: Achaemenid, Bauhaus, and Palladian, to evaluate StyleGAN's effectiveness. Through three experiments employing qualitative and quantitative methods, StyleGAN's performance in generating images from these diverse architectural datasets was assessed. The Achaemenid style was chosen for its visual uniformity, Bauhaus for its distinctive features, and Palladian for its diversity. StyleGAN successfully generated clear and coherent images across all datasets, showcasing its ability to learn and replicate architectural styles with minimal noise and effective pattern integration. Table 1 below shows mostly used algorithms and design processes.

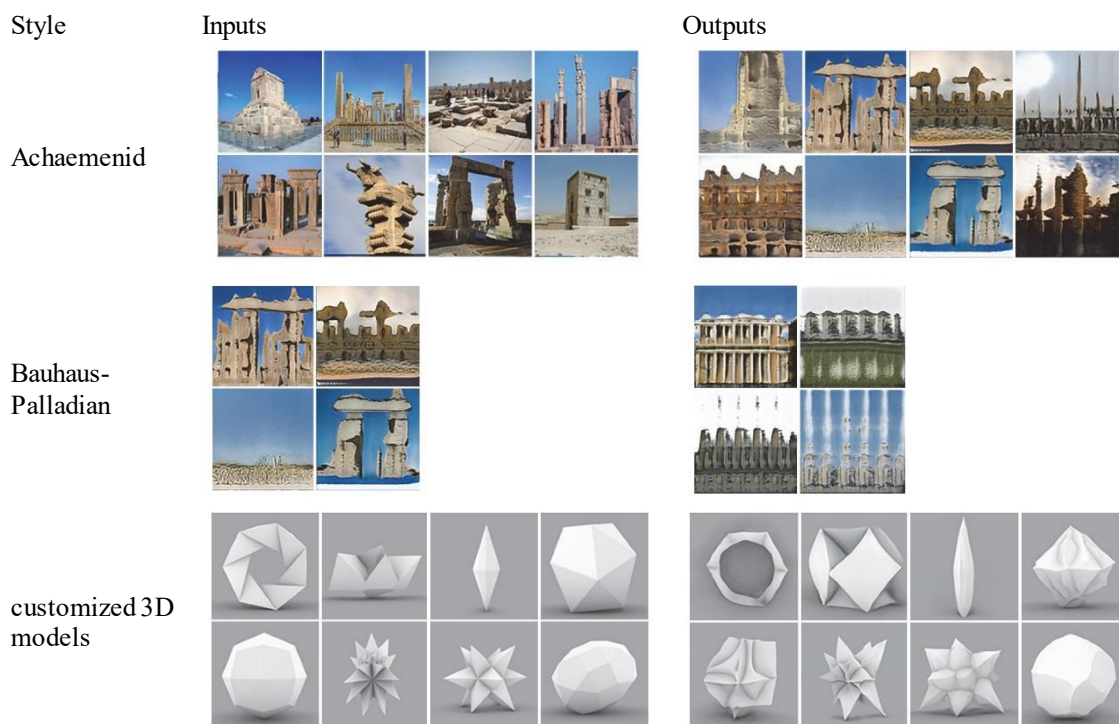


Fig. 6. Beginning Images, Stages of Development During Epochs, and Final Images for Each Style [29].

Table 1. Algorithms and design processes

The Case Study	Algorithm Type	The process	Input Data	Output Data
Architectural Drawings Recognition and Generation through Machine Learning	Generative Adversarial Networks (GANs) – 'pix2pix' and 'Pix2pixHD'	Architectural drawings transformation and recognition	Labeled image pairs, colored floor plans	Converted floor plans to maps and vice versa, enhanced architectural plan recognition
3D Graph Convolutional	3D Graph Convolutional	Analyzing and enhancing creativity	Architectural models database	Classification of models into styles (Baroque, Cubist),

Neural Networks in Architecture Design	Neural Networks (GCNN)	in 3D architectural modeling		linking features to style and functionality
Deep Learning as Heuristic Approach for Architectural Concept Generation	CyleGAN	Translation between architectural styles	Images of the Sagrada Familia	Translated architectural styles, evaluated through objective and subjective metrics
Deep Convolutional Generative Adversarial Network to Investigate the Virtual Design Space of Historical Islamic Patterns	Deep Convolutional Generative Adversarial Network (DCGAN)	Exploration of design space of Islamic design	Internal structures of Islamic designs	New designs in line with Islamic geometric patterns
Architectural Form Explorations through Generative Adversarial Networks Predicting the potentials of StyleGAN	StyleGAN	High-resolution image generation of architectural forms	Building images classified into Achaemenid, Bauhaus, and Palladian styles	Generated images representing distinct architectural styles

3.6 Critical Analysis of The Case Studies

Through a critical analysis of these case studies, it becomes evident that advanced AI technologies have made a profound impact on the field of architectural design and analysis. Each study provides valuable and distinctive insights into the diverse capabilities and wide-ranging applications of these technologies.

1. Exploring GANs in Architecture sheds light on the practical implementation of 'pix2pix' and 'Pix2pixHD' in the transformation and recognition of architectural drawings. The utilization of these GANs presents a remarkable advancement in digital architectural design, enabling a more intricate and comprehensive depiction of architectural plans. Also, effectively bridges the divide between machine learning and human cognition, particularly in comprehending abstract concepts, thereby establishing a solid groundwork for future investigations at the convergence of AI and architecture.
2. 3D Deep Learning in Architecture by Utilizing GCNNs, explored the potential of enhancing creativity through 3D modeling. By linking 3D model features to architectural styles and aesthetics, GCNNs demonstrate their ability to recognize and replicate complex architectural concepts. In addition to, show cases AI's technological advancements and emphasizes its intuitive assistance for architects in applying style and aesthetics.
3. AI and Creativity in Architecture by focusing on the iconic Sagrada Familia, demonstrated AI's role in interpreting and replicating architectural styles. The use of cycleGAN algorithm and a mix of objective and subjective evaluation methods underlines the nuanced capabilities and challenges of AI in architectural design. The work emphasized the importance of targeted training datasets and suggests a collaborative approach between automated and human evaluations in AI-generated designs.

4. Revolutionizing Islamic Architecture with DCGAN, showed the innovative use of DCGAN in reinterpreting traditional Islamic architecture. By generating designs that are both authentic and innovative, the potential of digital technologies in preserving and evolving traditional design styles. This approach influenced by Gilles Deleuze's philosophy, bridges historical designs with modern architectural innovation, continuing the legacy of ancient craftsmanship.
5. by Testing StyleGAN across various architectural styles, Architectural Image Generation with StyleGAN highlighted its ability to generate clear and coherent images, reflecting its strength in learning and replicating architectural styles with minimal noise. This finding is pivotal in demonstrating how AI can synthesize diverse architectural inputs into coherent and innovative outputs, enhancing style integration in design.

4 Conclusion

The integration of neural networks and architecture operates across multiple levels: design, construction, and behavior. Neural architecture, a novel approach that combines human and machine capabilities, uncovers hidden patterns in the design process. Design thinking incorporates established and new patterns, striking a balance between novelty and familiarity in architecture. Artificial neural networks play a vital role in construction, facilitating the creation of smart buildings that integrate technology, reduce costs, and enhance energy efficiency. Neuroarchitecture, focusing on behavior, investigates how built environments impact the human brain, necessitating experimental research using brain imaging technology. The case studies collectively demonstrate a significant advancement in architectural design through the integration of artificial intelligence and machine learning. By showing case the transformative impact of AI in architecture, highlighting how advanced technologies like GANs and GCNNs improve aesthetics and functionality while bridging the gap between traditional and modern design approaches. This integration signifies a shift towards more innovative, efficient, and exploratory design processes, paving the way for future advancements in the field.

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