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Integration and Optimization of Artificial Intelligence Solutions in Modern Architectural Design

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Abstract: AI will not replace architects; On the contrary, it will improve their ability and efficiency. While AI can automate everyday tasks, optimize designs, and provide advanced analytical insights, the creativity and complexity of architectural design requires nuanced judgment and creative intuition that only human architects can provide. The architects use a unique blend of creativity, experience and emotional intelligence to design Spaces that resonate with humanity at a deep level. By analyzing generative AI to revolutionize the architectural design process, this paper emphasizes that the design of artificial intelligence system should be led by the needs of architects and adjust at any time according to the changes of specific architectural context through the architect-specific human-computer interaction relationship. Organize generative AI functions such as sketch rendering, 3D models generation, trend analysis, and text generation of images or reports by building a design framework.

Keywords: Generative AI； Artificial Intelligence; BIM, Digital twins, Extended Reality (XR) and Internet of Things (IoT)

INTRODUCTION

Modern architecture, also known as modernist architecture, is an architectural movement and style that, in the 20th century, fell between the early Art Deco and the later postmodern movement. Modern buildings based on new and innovative construction technologies (especially the use of glass, steel and concrete); Principal functionalism (i.e. form should follow function); Embrace minimalism; And refuse to decorate. [1] According to Le Corbusier, the movement has its roots in the work of Eugene Viollet le duc, [2] while Mies van der Rohe was deeply inspired by Karl Friedrich Schinkel. [3][4] The movement emerged in the first half of the 20th century and dominated after World War II until the 1980s, when it was gradually replaced by postmodern architecture as the dominant style of institutional and corporate architecture. Artificial Intelligence (AI) is redefining architecture and driving unprecedented efficiency, innovation, and sustainability. Architects can explore countless design possibilities in seconds with AI-driven generative design and push the boundaries of creativity while optimizing every aspect of a project. From automated drafting to real-time updates for building information modeling (BIM) to energy consumption analysis, AI streamlines workflows and enables architects to focus on creating visionary designs.

Project management is also in the development of AI to ensure timely and budget-friendly completion through intelligent scheduling, resource allocation, and risk prediction. Enhanced collaboration and seamless data integration improve communication between architects, engineers, contractors and clients, resulting in smoother project execution.

AI promotes sustainability through energy efficiency insights and eco-friendly material recommendations. Immersive virtual reality (VR)[5] and augmented reality (AR)[6] visualizations provide customers with unrivalled spatial experiences of the future, while predictive data insights drive informed decision making and personalized solutions. As this technological revolution continues, the future of architectural design will continue to evolve and embrace innovation.

Related Work

The idea of traditional architectural design generation

Modern architecture emerged at the end of the 19th century, stemming from a revolution in technology, engineering, and building materials, as well as a desire to move away from historic architectural styles and invent something purely functional and new. The materials revolution came first, using cast iron, drywall, sheet glass, and reinforced concrete to build stronger, lighter, and taller structures. The cast sheet glass process was invented in 1848 and allowed for the manufacture of very large Windows. Joseph Paxton's Crystal Palace at the Great Exhibition of 1851 was an early example of iron and sheet glass architecture, followed by the construction of the first glass and metal curtain wall in 1864. Together,

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these developments led to the first steel-framed skyscraper, the ten-story Home Insurance Building in Chicago, built in 1884 by William Le Baron Jenney[7] and based on the work of Viollet le Duc(Figure 1).

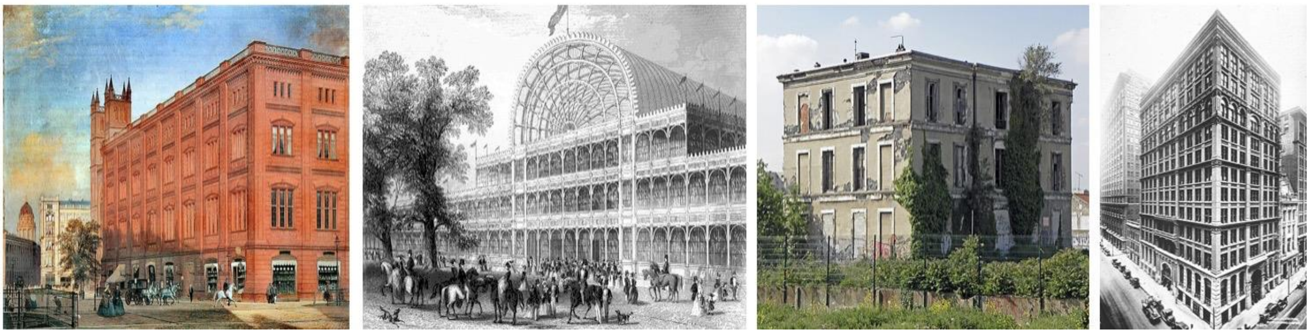

Figure 1: Classic style of traditional architecture in the 19th century

Traditional architecture is a design influenced by the cultural heritage of a region, using local materials, techniques and forms passed down from generation to generation. It embodies the adaptation of buildings to specific climatic, environmental and social conditions, resulting in buildings that are inherently sustainable and rooted in the identity of the community [8]. Traditional building forms vary widely around the world, from wood-framed houses in Japan to adobe buildings in the American Southwest, each building responding harmoniously to its unique environment.

It's important to acknowledge that we think of architecture as a "living tradition," created by Steve Mouzon, architect and author of Raw Green and Living Tradition. In his book, Living Tradition: Bahamian Architecture, he explains:

For most of human history, traditions were transmitted orally, without paintings or words, sometimes songs, sometimes poems or often just stories. The heartbeat of living tradition is four simple words: "We do it because......" [9] If every pattern in the language of urbanism or architecture were expressed in these terms, everyone could rethink, and traditions could spread far and wide. Living tradition is the original crowdsourcing.

This means that designing traditional buildings is not about copying old ones - although when designed and executed with skill and craftsmanship, "period" buildings can be excellent. The core of traditional architecture can be any type or style, aiming to learn from the history, culture of the area and build an appropriate building that applies this knowledge. It reflects the lifestyle and values of the people it serves. It is characterized by a deep respect for craftsmanship and construction methods that demonstrate the skills and knowledge of local artisans.

There is a reason that traditional architecture accepts the way things are done, whether we need to be able to explain it or not: the roof slope breaks in a certain way because it drains water better, or holds snow better; The window is built in a certain way because it can withstand the change from hot to cold; The building is proportional in a certain way because it feels better, and we relate to its scale on a human level.

The impact of artificial intelligence on the design process

With AI-driven generative design tools, architects can quickly generate many design alternatives by setting specific parameters, optimizing layouts, and selecting innovative and practical materials. These tools also use environmental data to recommend sustainable materials and best building directions to improve energy efficiency and project sustainability [10-12]. This accelerated and improved design approach speeds up the process and improves the quality of the final design.

Artificial intelligence offers significant advantages to customers and construction companies. Customers benefit from virtual and augmented reality tools that help them visualize and interact with designs prior to construction for better decision making and satisfaction. Construction companies benefit from increased productivity, as AI can automate tedious tasks, minimize errors, and improve cost and time estimates. Ai also facilitates better collaboration by integrating various data sources into a unified platform, so that companies can more effectively deliver exceptional projects and expand their customer base.

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Figure 2: Evolution of digital twins (BIM, BAM, BOOM) in architectural design

Artificial intelligence is augmenting building technologies such as BIM, digital twins, Extended reality (XR) and the Internet of Things (IoT)[13]. In BIM, AI facilitates real-time updates, predictive maintenance, and automatic collision detection, simplifying the construction process and ensuring accurate, up-to-date models. Digital twins benefit from AI's ability to simulate scenarios, predict outcomes, and optimize building performance for more efficient and sustainable operations.

Ai is also transforming XR technologies, including VR and AR, by providing more immersive and interactive design experiences. This allows architects and clients to visualize and modify designs in real time, resulting in better decisions and increased customer satisfaction. Ai enhances iot by analyzing data from connected devices to optimize building management systems and improve energy efficiency, safety and occupant comfort. The integration of AI with these technologies enhances the entire building lifecycle, making structures smarter, more efficient, and adaptable to future needs.

Modern Architectural Design and Generative AI

Architectural designers often do not possess such concrete concepts and clear logic. Architectural design is a complex and lengthy process. Architects often start by collecting relevant examples and gradually develop a vague vision that forms the basis of an architectural proposal. In the process of architectural design, in addition to the aesthetic and other internal forces, there are also external influences, regulations and other forces. A variety of complex factors lead to the architectural design will not be completed at one time, and the architectural form does not have the exact design logic, which needs to be iterated several times, scheme screening, and finally gradually improved. Early generative design methods prematurely constrict architectural design within a framework, resulting in a lack of creativity in the resulting results.

Since 2014, the emergence of "Generative Adversarial Network" (GAN) has led the vigorous development of GAI [14], further enhancing the freedom of building generation. The development of generative artificial intelligence can be roughly divided into three stages: the early stage (from 1950 to 1990), due to technical limitations, only used for small-scale research; In the middle stage (1990-2010), due to the emergence of deep learning algorithms and the improvement of computing equipment, prototype research on GAI technology began to appear, such as Microsoft's simultaneous interpretation based on deep neural networks (DNN) in 2012[15]; In the rapid development stage (from 2010 to now), due to the emergence of GAN, generative AI technology has been innovated, and a large number of AI interactive generated content has emerged.

Figure 3: Architect's automated floor plan designed for architects through generative human 3d work intelligence

Generative AI is being applied to a range of construction-related applications, including data quality enhancement, building layout generation, 3D printing path generation, and more. With the development of diffusion models and the GPT family, generative AI has incredible potential to drive a paradigm shift and revolutionize the construction industry over time [16]. Due to the dynamic nature and complexity of construction projects, the design scheme is constantly developing and changing. At the same time, because it is composed of multiple feedback systems, the condition change of a certain part will lead to unforeseeable overall changes, which makes it difficult for traditional machine learning schemes to adapt. A deeper understanding of generative AI will help expand the efficiency, quality and scope of application of generative AI in the field of architectural design.

Generative AI and Architectural Design

Generative AI Enhances Architectural Design

AIGC technology is one of the leading technologies in the field of artificial intelligence today, which has the ability to generate new data in various fields, such as text, images, audio, etc. This ability refers to the ability to create novels, works of art, paintings, and music just like human beings by automatically generating content through artificial intelligence. AIGC relies heavily on generative AI techniques, which aim to infer some actual data distribution. For example, the joint probability distribution of inputs and outputs P(X, Y) or P(Y), which are often derived from higher-dimensional Spaces. By doing so, the generative model produces a new synthetic sample in a given situation, such as given a target value Y, generates a new pair of characteristic observations (X, Y) or a new observation X, i.e. automatically generates a new design or forms a prediction (discrete class or continuous value) [17-19].

In building design, by analyzing large amounts of building data and design patterns, AIGC can generate multiple design options that can be optimized for specific needs, such as functional layout, structural stability, energy efficiency, and aesthetics. The application of this technology not only helps to reduce the repetitive labor of designers, but also can push the construction industry in a more intelligent and sustainable direction.

Mainstream Technology

In the field of architectural design, it mainly involves the generation technology of image and model, and its algorithm framework is mainly divided into the following three categories (Figure 5):

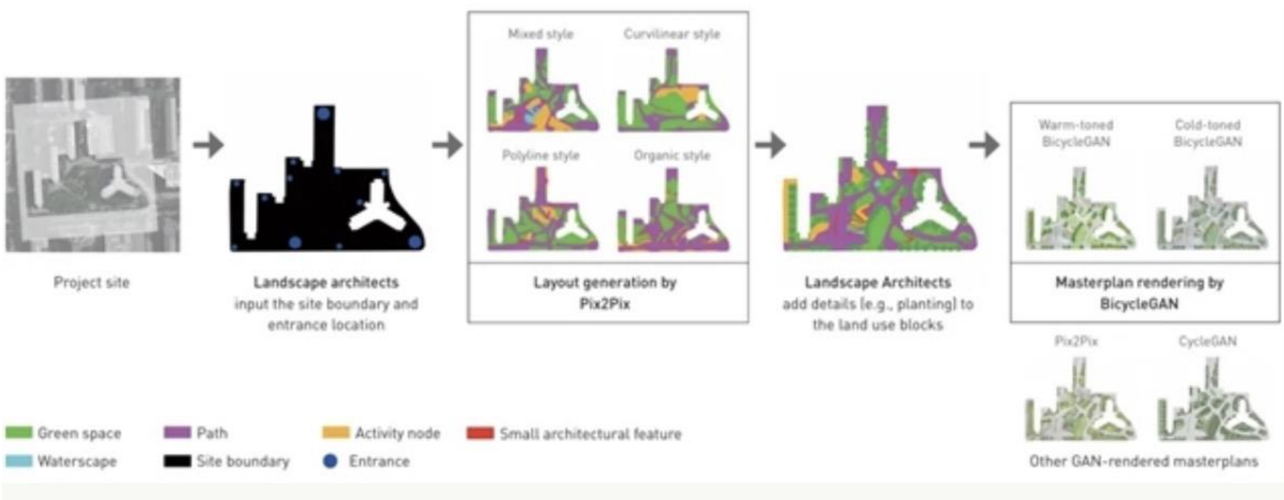

Figure 5: Example of layout generation and flat rendering in a GAN workflow

- Diffusion Model: This model is usually used for tasks such as image generation. Diffusion models capture image data by modeling the way data points are noised in the underlying space, specifically, they typically use Markov chains trained in variational reasoning and then reverse diffusion to generate natural images. Some common image generation algorithms and software use this framework, such as Stable Diffusion model (DALL-E)[20], MidJourney, etc.
- Generative adversarial network: Gans are composed of two neural networks, the first network is called a generator for generating false samples, and the second network is called a discriminator for identifying whether the input sample is true. Through the confrontation of the two, the generator continuously improves the ability of generating samples, and the discriminator continuously improves the ability of discriminating, so that the final generated samples are more and more close to the data distribution of real samples. GAN is not only simple in structure, but also can be used to generate completely new samples and has been the main method of application for a long time. Gans include some commonly used variants such as conditional GAns (CGans), pix2pix, StyleGAN, CycleGAN, and others.
- Variational Autoencoder (VAE) [21]: Learns a low-dimensional representation of the input data by encoding it into a compressed latent variable space and then reconstructing the original data from this compressed representation. VAEs encode and decode processes by using a probabilistic approach, which allows them to capture potential structures

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and changes in the data and generate new data samples from the potential Spaces learned. It is often used for anomaly detection, data compression, image and text generation and other tasks.

The Application Status of Generative AI to Enhance Architectural Design

Site Analysis

1. Building image recognition for real building recognition, there are many tasks in architectural design that need to accurately collect facade features, such as energy consumption simulation of existing buildings, renovation of old buildings, urban renewal, etc. In the past, it mainly relied on real building measurement, which is a time-consuming and labor-intensive process. The image translation and segmentation capabilities of generative AI can quickly extract elemental features from architectural images to achieve simple calculations. One type of research builds a framework through grammar-based edge detection or CNN learning-driven methods to automatically detect the ratio of facade to window to wall, predict building height, and identify building area in street view images. The other category improves the existing case segmentation algorithms, such as SOLOv2, Mask R-CNN, etc., to achieve window segmentation of building facades, eliminate image distortion and occlusion of building facades, and realize feature extraction of building facades, providing basic data for building energy consumption simulation, urban renewal and other scenes [22].

For the recognition of architectural drawings, architectural drawings are widely used and contain detailed information, which mainly relies on manual calculation of architectural drawings in the past, so the drawing recognition technology has unique advantages in the reconstruction and high-precision restoration of buildings. At present, YOLO series model and R-CNN model are often used to detect target entities in drawing element recognition. Some use similar CNN to classify engineering drawings, such as electrical drawings, mechanical engineering, etc. The other part is used to identify important elements in architectural drawings, such as structural, decorative, functional elements in architectural plans based on generative adversarial networks (GAN), or to provide data support for the automatic generation of subsequent BIM.

2. Environmental perception modeling Generative AI can be combined with architectural space to acquire features from spatial analysis and data and predict a series of evaluation indicators and results based on historical and current data. The parameters of most simulation tools are complex, time-consuming and costly. Quantitative analysis based on generative algorithm model can, on the one hand, greatly shorten the calculation time, so as to evaluate the form, space and layout performance of architectural schemes more quickly, so as to optimize schemes conveniently in the early stage of design. On the other hand, the model can be trained through real data and then used for the prediction of the design scheme to achieve more accurate prediction.

In terms of behavior analysis, the activity distribution and behavior patterns in the built environment are analyzed by inputting building plans and using generative adversarial networks (such as pix2pixHD and GAN) to generate behavioral heat maps. For example, Zheng Hao et al. trained pix2pixHD based on images to generate thermal maps of behavioral vitality of subjects in different sections of the built environment through input of the plan of the built environment, so as to explore the relationship between the built environment and the activities of cyclists in the environment, so as to identify areas where regional vitality can be improved (Figure 6) [23]. Similarly, the ARD team at Foster + Partners generated thousands of floor plan datasets through parametric modeling, then performed spatial and visual connectivity analysis, and trained them using the full convolutional U-Net network and Pix2Pix for spatial and visual connectivity assessment.

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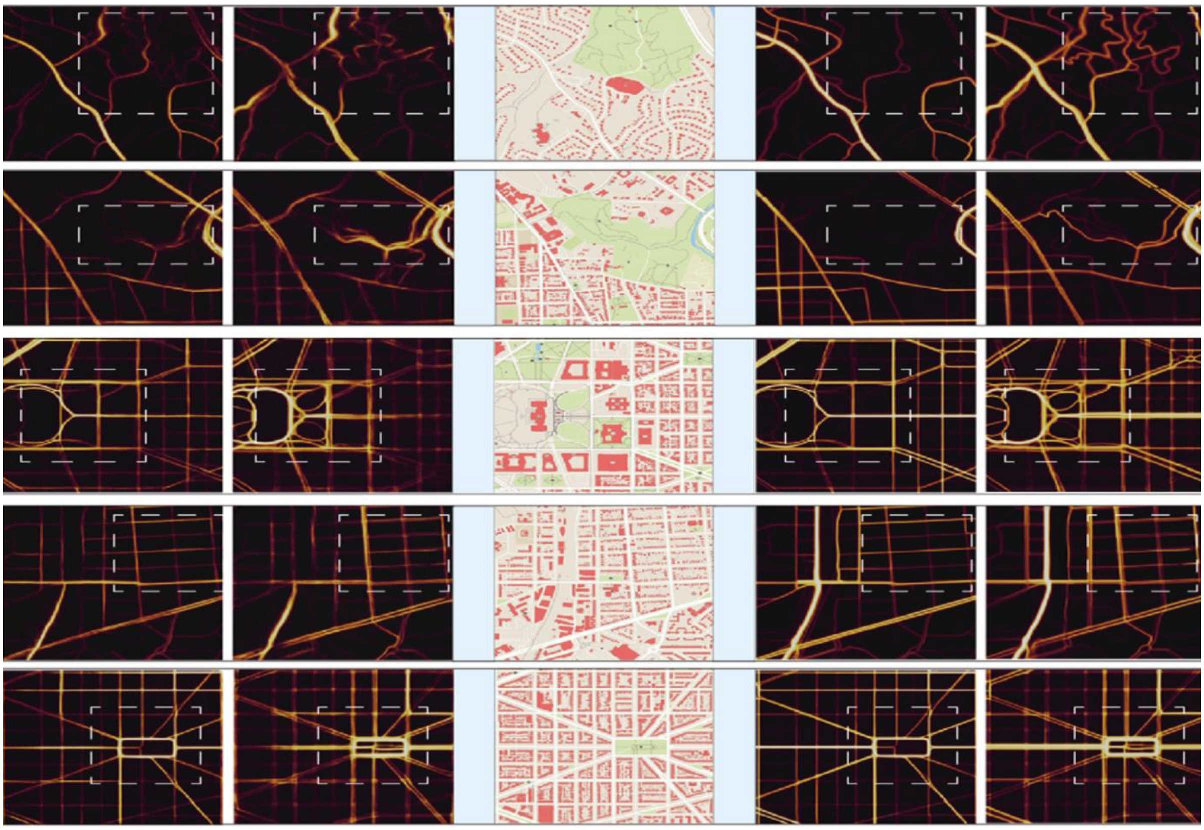

Figure 6: Operational thermal prediction diagram of the built environment

In terms of environmental performance calculations, generative AI can often be used in proxy models. For example, the daylight simulation agent model pairs floor plans containing geometric and daylighting information into generative AI, and the trained model is used to predict the daylighting performance of the building design. Part of the research focuses on multi-modal feature fusion, such as using the combination of pixels and vectors to represent the plane, elevation, reflectivity, transmittance and other building conditions, to establish a multi-modal feature fusion mechanism, so as to quickly evaluate the daylight performance of the design in the early stage of building design. In addition, GAN-based combining existing building performance calculation models with specific data from context-aware designs uses performance objectives as a guide to generate enhanced building performance calculation models.

Solution Generation

1. Architectural concept generation with the development of image generation technology, architects or construction companies gradually adopt generative AI technology to generate architectural concept intention drawings at the early stage of architectural design for rapid trial and error. The algorithm with StyleGAN, CycleGAN, Stable Diffusion and Controlnet as the core is mainly used. Firstly, the intention map is collected, the data set is built, and the pre-training model of this algorithm is trained or fine-tuned. Finally, through the input text to generate images, image to generate images, local redrawing and other methods to achieve the generation of architectural concepts. This approach has been explored by a number of design firms in the architecture industry, such as Coop Himmelb(l)au's cloud enhancement project, GAM Design's vision of mood architecture, etc.), and Zaha's image collection created by Zaha Hadid Architects.

2. Text-generated image is one of the most important cross-modal generative models. In the early stage of design, there is no exact design intention, so it is often possible to quickly generate the image through the form of text-generated image. Manas Bhatia's conceptual project "AI X Future Cities" uses MidJourney to generate architectural visions with such prompts as "tower of the future," "Utopian technology," "symbiosis," and "bioluminescent materials." Architect Karisma Shoker used Midjourney's programming techniques to shape the envisioned entrance to Atlantis. Green Clay Architects uses AI tools to combine modern engineering with traditional Persian aesthetics to design a stadium made of concrete, wood and glass. SaT Studio envisioned a house made of ice to contrast with the hot climate of southern Iran; Designed a skyscraper made of suspended rock on the streets of Paris. The method of generating images from text often faces the problem of weak controllability of text, so it is only suitable for the situation where the architect has no clear idea of the architectural design scheme. The method of generating images from text often has the problem of weak text control, so it is usually

more suitable when the architect has not formed a clear idea of the architectural design scheme.]

3. Image generation Image improves the controllability of the early design, and generates a rendering image by inputting one or more images as the guide of content and style. Common image generation technology can be used in the following two cases:

- Sketch generation rendering: First establish the data set of sketch and architectural image pairing and realize the automatic generation of architectural image by training CycleGAN and cGAN.
- Generate the rendering of the grass model screenshot: by entering the grass model image in Sketchup or Rhino, use ControlNet to generate the corresponding architectural rendering. Of course, the input information in this step is more diverse, which can be hand-drawn sketches, model sketches, real architectural images, or non-architectural item combinations, etc.

Different information inputs and different algorithm choices will affect the final generated architectural rendering. In addition to input a complete picture, it is also possible to use partial redrawing to alter a single picture, match the picture with the position to be modified, and the generative AI will regenerate the part to be modified.

4. Another type of architectural concept involves the general planning of the interior of the site and the interior of the building. Spatial layout planning in architectural design requires a deep understanding of topological spatial relationships. Generative AI, due to its extensibility, can input flexible data sources to realize the generation of architectural spatial layout. Early automated spatial layout often used shape syntax, genetic algorithm, etc., but it often took too long to find the optimal solution. At present, by inputting the existing boundary or site conditions, the spatial relationship is represented by the graph structure, and the training is generated by GAN or diffusion model to complete the next design. For example, in the study of build-gan, the architectural representation form of Voxel Graph is proposed, and cross-modal graph neural network is used as a generator for training in the generative adversary-network to achieve 3D space division with functional calibration [24].

In the functional layout of a single building space, an empty room is divided into several functional areas using cGAN, and then a fully connected network is trained to place furniture in the corresponding functional areas to complete the furniture layout of the room. In addition, the research of spatial planning generation is also used to search for similar spatial layouts, and applications often extract the topological structure of the functional layout of plane or model data, and then search the database to find the required design. For example, by entering an image or sketch, the type of query is automatically determined, and similar floor plan images are retrieved from the database.

CONCLUSION

Generative AI revolutionizes the architectural design process, emphasizing that the design of artificial intelligence systems is dominated by the needs of architects through architect-specific human-computer interaction, and can be adjusted at any time according to changes in the specific architectural context. Organize generative AI functions such as sketch rendering, 3D models generation, trend analysis, and text generation of images or reports by building a design framework.

For different task requirements, the design process framework is often different. Yang Junyan's team built an intelligent design module of the three-dimensional form of urban blocks through artificial intelligence methods such as evolutionary algorithm, adaptive algorithm and supervised deep learning. First, they built a base computing module to collect peripheral information and intelligent control module and proposed a relatively complete technical process of the intelligent design of the three-dimensional form of urban blocks [14]. Anca-Simona Horvath, incorporating the evolo Competition's design scheme process, details how to design at the concept stage using text-to-text, text-to-image and image-to-image. For example, she dissects three linguistic levels: architectural discourse, programming discourse, and annotation, and explains how they are used in design. In addition, some studies have proposed a rapid design process: generate a plane concept map from a black and white sketch, process it into a depth map, convert the depth map into a 3D point cloud model through modeling software, and then generate a rendering map from multiple perspectives, so as to realize the rapid conception and controllable generation of architectural renderings based on text descriptions.

Despite AI's transformative potential in architecture, several challenges have prevented its widespread adoption. The initial investment required for AI technology and infrastructure is a significant hurdle, which can be daunting for many companies, especially smaller ones. Another obstacle is the learning curve associated with AI tools, which requires training and upskilling. Resistance to change is still common in the industry, as some professionals who are used to traditional methods may be slow to embrace new technologies.

However, these challenges are not insurmountable. Companies can take a phased approach, starting with smaller projects to gradually integrate AI and build confidence in its capabilities. Partnerships between AI providers and construction companies can tailor solutions to specific needs, reducing cost and complexity. Investing in strong training programs will equip the workforce with essential skills and foster a culture of innovation and adaptability.

Cloud-based AI services can alleviate the need for heavy on-premises infrastructure, making advanced AI tools more accessible to companies of all sizes. By strategically addressing these challenges, the construction industry can fully harness the potential of AI, paving the way for a more efficient, innovative and sustainable future.

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