https://doi.org/10.51483/IJARP.3.2.2023.12-48 ISSN: 2788-5046

SvedbergOpen
DISSEMINATION OF KNOWLEDGE

International Journal of Architecture and Planning

Publisher's Home Page: https://www.svedbergopen.com/

Review Article **Open Access**

Leading-Edge Technologies for Architectural Design: A Comprehensive Review

Nitin Liladhar Rane[1*], Saurabh P. Choudhary[2] and Jayesh Rane[3]

[1]University of Mumbai, Mumbai, India. E-mail: nitinrane33@gmail.com
[2]University of Mumbai, Mumbai, India. E-mail: ar.sourabh@gmail.com
[3]University of Mumbai, Mumbai, India. E-mail: jayeshrane910@gmail.com

Article Info

Volume 3, Issue 2, September 2023
Received : 13 July 2023
Accepted : 18 August 2023
Published : 05 September 2023
doi: 10.51483/IJARP.3.2.2023.12-48

Abstract

In architecture, the incorporation of state-of-the-art technologies is crucial for advancing design methodologies and achieving groundbreaking solutions. This exhaustive review delves into a diverse array of cutting-edge technologies reshaping the architectural design landscape. The scrutinized technologies not only amplify the efficiency of design processes but also contribute to the development of sustainable, adaptable, and technologically advanced built environments. Commencing with an exploration of Artificial Intelligence (AI) in architectural design, the paper underscores how machine learning algorithms and neural networks are revolutionizing the conceptualization and optimization of architectural forms. Emphasis is placed on AI's capacity to analyze extensive datasets, predict design trends, and generate alternative designs, thereby fostering creativity and streamlining the design process. The immersive potential of Virtual Reality (VR) and Augmented Reality (AR) in architecture is thoroughly examined. The paper elucidates how these technologies are not only transforming the visualization of designs but also facilitating collaborative design processes, enabling stakeholders to experience spaces before the commencement of construction. Parametric Design and Computational Modeling are scrutinized extensively, showcasing their pivotal role in crafting intricate and optimized structures. The exploration extends to Building Information Modeling (BIM), elucidating its significance in promoting collaboration, reducing errors, and streamlining the entire building lifecycle. Moreover, Sustainable Building Materials and Technologies, Generative Design, ChatGPT, 3D/4D/5D/6D Printing, Responsive Architecture, Drones and Aerial Imaging, Digital Twin Technology are focused. Smart Building Systems, integrating IoT technologies, are explored for their role in enhancing building performance, energy efficiency, and occupant comfort.

Keywords: *Architectural design, Building information modelling, Construction industry, Artificial intelligence, Virtual reality, Augmented reality, Parametric design, Computational modeling, 3D printing*

---

[*] *Corresponding author: Nitin Liladhar Rane, University of Mumbai, Mumbai, India. E-mail: nitinrane33@gmail.com*

1. Introduction

In the dynamic realm of architectural design, the swift progression of technology has not only transformed the way architects conceive and implement their ideas but has also ushered in a new era of possibilities and efficiencies (Weber *et al.*, 2022; Liu *et al.*, 2022; Žujovi *et al.*, 2022; Pylkkänen *et al.*, 2023). This research paper embarks on a comprehensive journey through cutting-edge technologies that have become integral to contemporary architectural practices. From Artificial Intelligence (AI) and Virtual Reality (VR) to Sustainable Building Materials and 3D Printing, the architectural landscape is currently undergoing a transformative wave, challenging traditional methodologies and presenting unprecedented avenues for innovation. At the forefront of this technological revolution is Artificial Intelligence (AI), a transformative force fundamentally altering the design process (Zhang *et al.*, 2023; Pena *et al.*, 2021; Yoshimura *et al.*, 2019; Zhang *et al.*, 2023; Ji, 2022; Bingol *et al.*, 2020). AI's capacity to analyze extensive datasets and extract meaningful insights has enabled architects to optimize design solutions, enhance spatial efficiency, and even predict environmental impacts. Machine learning algorithms, trained on historical architectural data, contribute to the creation of design patterns blending aesthetic appeal with functional efficiency (Tamke *et al.*, 2018; Cámara *et al.*, 2021; Millán *et al.*, 2022; Ploszaj-Mazurek *et al.*, 2020). This section explores how AI serves not just as a tool but as a design partner, influencing decisions from initial conceptualization to the final detailing of architectural projects. The immersive experiences offered by Virtual Reality (VR) and Augmented Reality (AR) have revolutionized how architects visualize and communicate their designs. VR enables stakeholders to immerse themselves in a three-dimensional representation of a building before it exists, fostering a deeper understanding of spatial relationships and design elements (Campbell and Wells, 1994; Ergün *et al.*, 2019; Chan, 1997, April; Frost and Warren, 2000). AR overlays digital information onto the physical world, offering real-time insights during the construction phase (Milovanovic *et al.*, 2017; Lee *et al.*, 2020; Shouman *et al.*, 2022; Sørensen, 2013; Penn *et al.*, 2005). This section delves into the impact of VR and AR on architectural visualization, collaboration, and the overall design workflow.

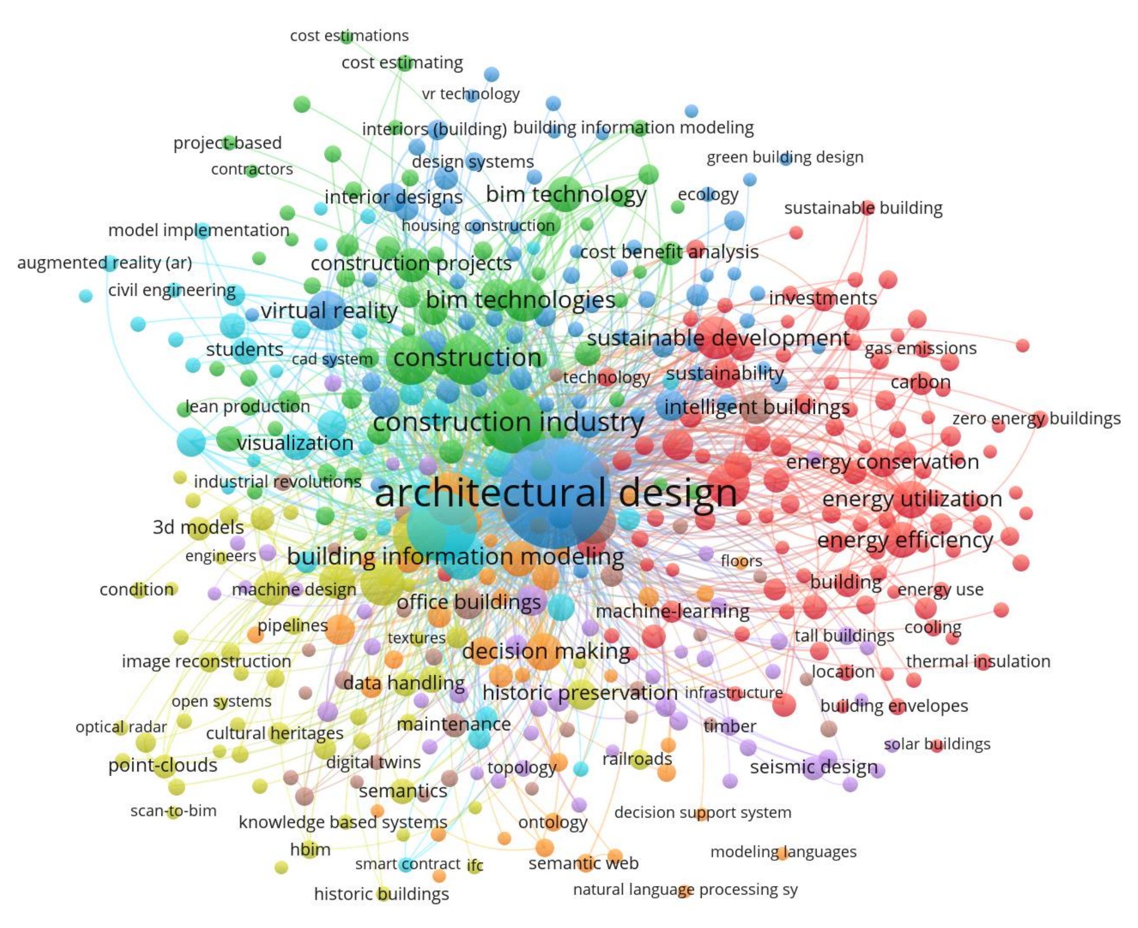

Figure 1: Co-occurrence Analysis of the Keywords in Literature

Parametric design and computational modeling have become synonymous with avant-garde architectural practices (Monedero, 2000; Na, 2021; Gu *et al.*, 2021; Schumacher, 2015; Bhooshan, 2017; Garcia and Jofre, 2012). The ability to manipulate parameters and variables within a digital environment allows architects to generate complex and innovative forms that respond to specific design criteria. Through algorithmic design processes, architects can explore myriad possibilities, optimizing for factors such as structural integrity, energy efficiency, and aesthetic coherence. This section examines how parametric design thinking is reshaping architectural discourse, pushing the boundaries of what is achievable in terms of form and function. Building Information Modeling (BIM) stands as a cornerstone in the digital transformation of the architectural industry (Penttilä, 2007; Dounas *et al.*, 2021; Tulubas and Arditi, 2017; Donato *et al.*, 2018; Mikhailov *et al.*, 2020; Thuesen *et al.*, 2010; Kiviniemi and Fischer, 2009; Chang and Shih, 2013; D'Amico *et al.*, 2020). It goes beyond conventional 3D modeling by incorporating data-rich elements that represent the entire lifecycle of a building. BIM fosters collaboration among various stakeholders, ensuring a seamless flow of information from design to construction and maintenance. This section explores the multifaceted benefits of BIM in enhancing coordination, reducing errors, and optimizing the overall efficiency of architectural projects. As the global community grapples with environmental challenges, architects are increasingly turning towards sustainable building materials and technologies to mitigate their projects' ecological footprint. This section investigates the latest advancements in eco-friendly materials, such as recycled composites and smart glass, and explores how these innovations are integrated into architectural designs to promote sustainability without compromising aesthetics or functionality. Figure 1 shows the co-occurrence analysis of the keywords in literature.

Generative design harnesses the power of algorithms to explore and generate numerous design iterations based on predefined parameters (Mukkavaara and Sandberg, 2020; Nagy *et al.*, 2017; Agkathidis, 2015; Singh and Gu, 2012; Caldas, 2008; Agkathidis, 2016; Azadi and Nourian, 2021; Kallioras and Lagaros, 2020; Caldas, 2006; Ostwald, 2010).

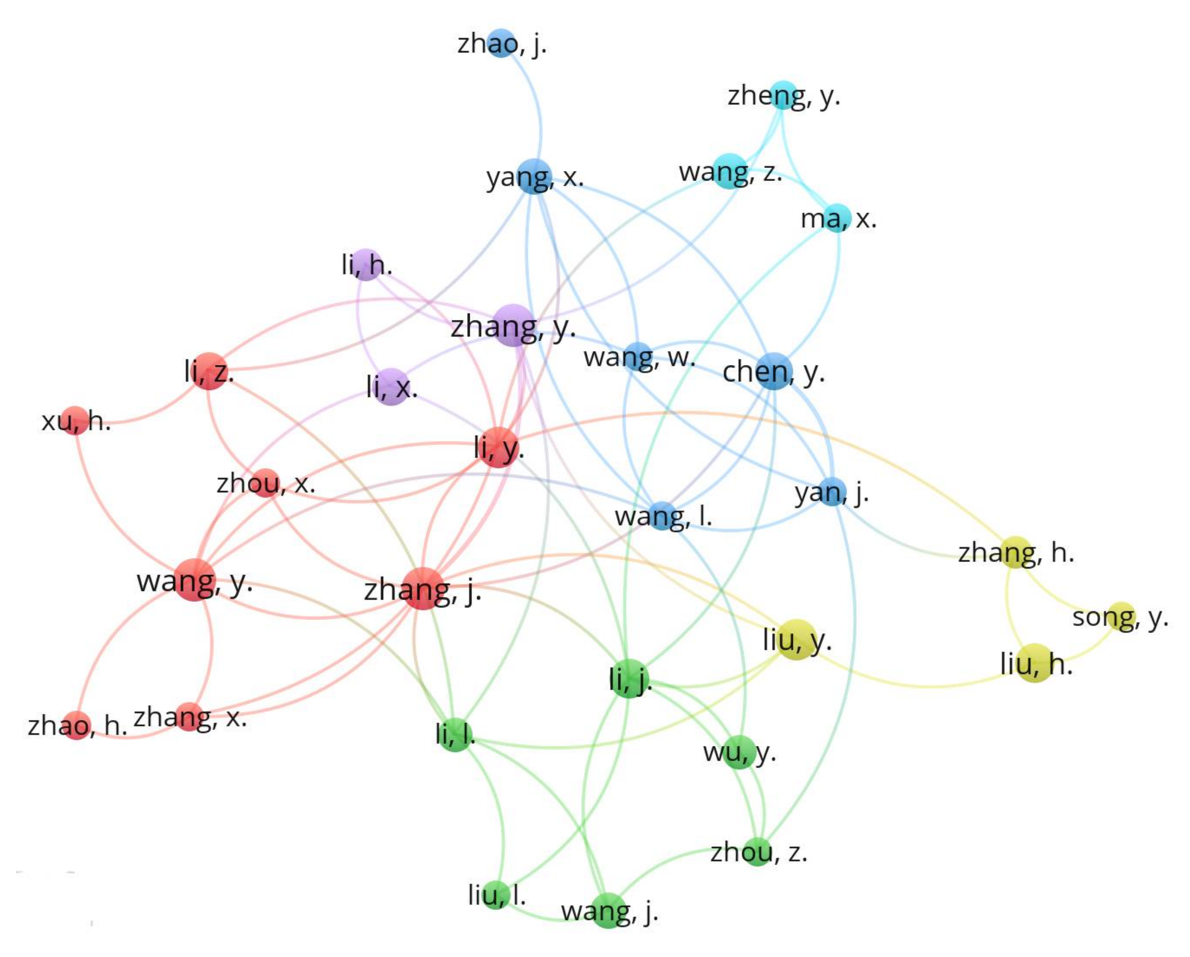

Figure 2: Co-authorship Analysis

This process not only accelerates the conceptualization phase but also encourages novel design solutions that might not be immediately evident through traditional methods. By mimicking evolutionary processes, generative design algorithms produce designs that are optimized for specific criteria, whether it be structural efficiency, energy performance, or spatial relationships. This section delves into the revolutionary potential of generative design in shaping the future of architectural creativity. The advent of 3D printing has transcended the realm of prototyping to become a viable method for constructing architectural components. From intricate facades to entire buildings, 3D printing offers unprecedented design freedom and resource efficiency (Talbott, 2006; Cohen, 2019; Niemelä *et al.*, 2019; Leach and Farahi, 2018; Žujovi *et al.*, 2022; Howeidy and Arafat, 2017; Naboni *et al.*, 2020). This section explores the evolution from 3D to 4D and 5D printing, where the fourth dimension introduces time as a variable, and the fifth dimension incorporates cost considerations. The implications of these printing technologies on architectural construction methodologies and design possibilities are thoroughly examined. The concept of responsive architecture encompasses structures that adapt and respond to their environment, occupants, or external stimuli. Incorporating sensors, actuators, and smart technologies, responsive architecture transcends static design to create dynamic, interactive spaces (Bukar and Othman, 2022; Gao and Fan, 2006; Swati and Priyanka, 2010; Shoaib *et al.*, 2012; Singh *et al.*, 2020; Bhawiyuga *et al.*, 2019; Hölttä and Otto, 2005). This section investigates how responsive architecture blurs the boundaries between the built environment and its users, creating spaces that evolve and cater to the ever-changing needs of society. Figure 2 shows the co-authorship analysis.

Drones have emerged as indispensable tools in architectural design and construction, providing a unique perspective from above (Zhou *et al.*, 2015;Cabuk *et al.*, 2022; Veerappan *et al.*, 2022; Kullmann, 2018; Lin and Sang, 2022; Rábago and Portuguez-Castro, 2023; Veerappan and Keong, 2022; Møller and Bjørn, 2016). Aerial imaging, facilitated by drones, allows architects to survey large areas, monitor construction progress, and gather data for site analysis. This section explores the transformative impact of drones on architectural practices, emphasizing their role in enhancing efficiency, safety, and data acquisition. Digital twin technology creates a virtual replica of a physical building or infrastructure, enabling architects to monitor, simulate, and analyze its performance in real-time. This section explores how digital twins contribute to informed decision-making throughout the building's lifecycle, from design and construction to operation and maintenance. The integration of Internet of Things (IoT) devices further enriches the digital twin experience, providing a holistic view of a building's performance and efficiency (Zhang *et al.*, 2021; Park *et al.*, 2020; Ozturk, 2021; Rausch *et al.*, 2020; Dezen-Kempter *et al.*, 2020; Ye *et al.*, 2022). The convergence of technology and architecture has given rise to smart building systems that optimize energy consumption, enhance security, and improve overall occupant well-being. This section delves into the integration of Internet of Things (IoT) devices, sensors, and automation systems in creating intelligent buildings that respond intelligently to the needs of their occupants. From energy-efficient lighting systems to climate control and security, smart building systems are transforming the way architects approach the design of modern structures. This comprehensive review explores the cutting-edge technologies that are reshaping the landscape of architectural design. From the integration of artificial intelligence to the exploration of sustainable materials and the advent of 3D printing, architects are presented with an unprecedented array of tools to innovate and redefine the built environment.

2. Methodology

This study employed a research methodology centered on an extensive literature review, involving a systematic exploration across diverse databases such as PubMed, IEEE Xplore, Scopus, and Google Scholar. The keyword searches were meticulously crafted to thoroughly investigate cutting-edge technologies in architectural design. Specific keywords tailored to each technology domain, such as "Artificial Intelligence in Architectural Design," "Virtual Reality (VR) and Augmented Reality (AR) in Architecture," "Parametric Design and Computational Modeling," "Building Information Modeling (BIM)," "Sustainable Building Materials and Technologies," "Generative Design," "3D/4D/5D Printing," "Responsive Architecture," "Drones and Aerial Imaging," "Digital Twin Technology," and "Smart Building Systems," were employed. The goal of the keyword search analysis was to identify and gather pertinent studies, articles, and publications from diverse sources. The literature review aimed to present a comprehensive overview of the current state of knowledge, highlighting key trends, challenges, and emerging themes within each technological domain. Furthermore, a bibliometric analysis was conducted to quantitatively assess the volume and impact of publications in these areas. This involved leveraging citation indices and evaluating publication trends across the selected databases. The insights derived from the literature review, keyword search analysis, and bibliometric analysis were synthesized to construct a conceptual framework for categorizing these technologies and facilitating a comparative analysis. The final synthesis provides recommendations for architects and industry practitioners, addressing challenges, proposing future research directions, and outlining best practices in the rapidly evolving field of architectural design technologies.

3. Results and Discussion

3.1. Artificial Intelligence (AI) in Architectural Design

AI has brought about significant transformations across various industries, and architectural design is no exception (Yoshimura *et al.*, 2019; Zhang *et al.*, 2023; Ji, 2022). The incorporation of AI into architectural design introduces a myriad of applications, elevating efficiency, creativity, and sustainability within the field. This shift is observable in multiple facets of architectural design, spanning from initial conceptualization through construction to post-occupancy evaluation. A key application of AI in architectural design is evident during the conceptual phase. AI algorithms, particularly those involved in generative design, play a pivotal role in generating diverse and innovative design options (Zhang *et al.*, 2023; Yoshimura *et al.*, 2019; Ji, 2022). Generative design involves using algorithms to explore numerous design possibilities based on predefined parameters and constraints. By leveraging AI in this context, architects can adeptly generate and assess a wide array of design alternatives, thereby saving time and resources during the project's early stages. Generative design algorithms, commonly integrated into popular design software, utilize machine learning techniques to analyze data and patterns from existing designs (Nagy *et al.*,2017; Azadi and Nourian, 2021; Ostwald, 2010). This enables architects to input specific criteria such as site conditions, functional requirements, and aesthetic preferences, empowering the algorithm to autonomously generate design options. For instance, Autodesk's generative design tool enables architects to explore hundreds or even thousands of design variations, providing a data-driven approach to design exploration.

AI also significantly contributes to optimizing designs for various parameters, including energy efficiency and structural stability. Given the contemporary emphasis on sustainable design, energy performance becomes a critical consideration. AI algorithms can analyze and optimize a building's orientation, shape, and material choices to enhance energy efficiency (Ji, 2022; Bingol *et al.*, 2020; Tamke *et al.*, 2018). For instance, machine learning models can simulate and predict the energy performance of different design options, aiding architects in making environmentally aligned decisions. Structural optimization is another domain where AI enhances architectural design. Advanced algorithms can analyze complex structural models, recommending optimizations for material usage, load distribution, and overall structural integrity. This not only ensures the safety and durability of the structure but also fosters the creation of more resource-efficient designs. Furthermore, AI facilitates the integration of parametric design in architecture. Parametric design involves using algorithms to create designs that respond to changing parameters (Na, 2021; Gu *et al.*, 2021; Schumacher, 2015; Bhooshan, 2017; Garcia and Jofre, 2012). Architects can utilize parametric design tools to craft dynamic and adaptive structures responsive to environmental factors, user behavior, or other contextual variables. For instance, a building's facade can dynamically adjust its shading elements based on the sun's path throughout the day, maximizing natural light while minimizing heat gain. Table 1 shows the Artificial Intelligence (AI) applications in architectural design.

Beyond the conceptual phase, AI and similar technology is increasingly employed in detailed design and documentation stages (Dezen-Kempter *et al.*, 2020; Ye *et al.*, 2022; Rane *et al.*, 2023a; Gautam *et al.*, 2023; Rane *et al.*, 2023b; Rane *et al.*, 2023c; Rane and Jayaraj, 2022). AI-powered automated drafting and documentation tools assist architects in the meticulous task of creating construction drawings. These tools comprehend the 3D model and generate 2D drawings, streamlining the design process and allowing architects to concentrate on more creative and complex aspects of the project (Cohen, 201; Niemelä *et al.*, 2019; Leach and Farahi, 2018). AI-powered tools are also impacting material selection in architectural design. With a vast array of available materials and their respective properties, choosing the right materials for a project can be overwhelming. AI algorithms can analyze the performance characteristics of materials, considering factors such as durability, thermal conductivity, and environmental impact. This analysis assists architects in making informed decisions about material selection based on the specific requirements of the project. Moreover, AI contributes to the improvement of project management and collaboration in architectural design. AI-enhanced project management tools assist architects in scheduling, resource allocation, and risk assessment (Eber, 2020; Zandi *et al.*, 2021; Patil, 2019; Wang and Hu, 2022; Xu *et al.*, 2022; Liu *et al.*, 2021; Zhang *et al.*, 2021; Tjebane *et*

Table 1: Artificial Intelligence (AI) Applications in Architectural Design

Application	**AI Techniques**	**Algorithms/ Models**	**Use Case**	**Challenges**
Generative Design	Genetic Algorithms, Neural Networks, GANs	Genetic Algorithms, Neural Networks, GANs	Automated design alternative generation, style exploration, and synthesis.	- Ensuring practical design compliance - Balancing creativity with functionality - Addressing interpretability of AI-generated designs - Managing biases in generated styles
Parametric Design Optimization	Genetic Algorithms, Optimization Algorithms	Genetic Algorithms, Optimization Algorithms	Optimizing design parameters for specific objectives such as cost reduction or energy efficiency.	- Defining accurate optimization objectives - Handling conflicting design objectives - Addressing computational complexity in large design spaces - Dependency on quality and completeness of input data
Image Recognition	Convolutional Neural Networks (CNNs)	CNNs	Recognition and interpretation of architectural elements, styles, and patterns from images.	- Handling variability in architectural styles - Ensuring accuracy and generalization to diverse datasets - Addressing interpretational challenges - Computational intensity in training and inference
Natural Language Processing	NLP Models like BERT, GPT	BERT, GPT	Understanding and generating textual descriptions of architectural designs, aiding in communication and documentation.	- Ensuring generated text aligns with design intent - Handling ambiguity and context in natural language - Fine-tuning models for architectural domain terminology - Addressing data privacy and security concerns in textual data
Energy Efficiency Analysis	Machine Learning, Simulation Models	Machine Learning, Simulation Models	Prediction and optimization of energy consumption in architectural designs, supporting sustainability goals.	- Accurate modeling of complex interactions affecting energy usage - Data availability and quality for training models - Balancing energy efficiency with other design objectives - Integration with existing design workflows and tools
Spatial Planning	Reinforcement Learning, Markov Decision Processes (MDPs)	Reinforcement Learning, MDPs	Intelligent spatial arrangement through learning optimal layouts and configurations based on predefined criteria.	- Defining appropriate reward structures for reinforcement learning - Handling high-dimensional state and action spaces - Ensuring real-world feasibility of AI-generated spatial layouts - Computationally intensive training and optimization processes
Virtual Reality (VR)	AI-driven VR platforms like Unity ML-Agents	Unity ML-Agents	Enhanced virtual reality experiences with intelligent virtual environments responding dynamically to user input.	- Development and integration of AI-driven VR tools - Ensuring real-time responsiveness and smooth user experience - Hardware and software compatibility for VR implementations - Learning curves for architects unfamiliar with AI-driven VR technologies

Table 1 (Cont.)

Pattern Recognition	Machine Learning, Pattern Recognition Algorithms	Machine Learning, Pattern Recognition Algorithms	Identification and analysis of design patterns, motifs, and features in architectural elements.	- Defining and labeling diverse design patterns for training - Sensitivity to variations and interpretations of design patterns - Adapting to evolving design trends and styles - Integration with existing design tools and workflows
Design Collaboration	AI-powered collaboration tools	AI-powered collaboration tools	Facilitation of collaboration among architects and stakeholders through intelligent document management and communication tools.	- Integration with existing collaboration and project management systems - User acceptance and training for AI-powered tools - Ensuring data security and privacy in collaborative environments - Customization to suit specific project requirements
3D Modeling Automation	Deep Learning, Autoencoder Models	Deep Learning, Autoencoder Models	Automation of 3D modeling processes through the use of deep learning techniques like autoencoder models.	- Ensuring accuracy and quality of AI-generated 3D models - Handling complex design geometries and details - Compatibility with existing 3D modeling tools and standards- User feedback and adjustments for AI-generated models

al., 2022). AI algorithms can analyze historical project data to identify potential risks and provide recommendations for mitigating them. Collaborative platforms, powered by AI, enable seamless work across different disciplines and geographic locations, enhancing communication and coordination.

Following equations represent fundamental concepts and algorithms frequently used in artificial intelligence;

3.1.1. Linear Regression Equation

$$y = mx + b$$

where,

y: Dependent variable

X: Independent variable

m: Slope of the regression line

b: Y-intercept of the regression line.

3.1.2. Logistic Regression Equation

$$P(Y = 1) = \frac{1}{1 + e^{-(mx + b)}}$$

where,

$P(Y = 1)$: Probability of the dependent variable being 1

e : Euler's number (base of the natural logarithm)

m and b : Parameters to be learned from the training data.

3.1.3. Support Vector Machine (SVM) Decision Function

$$f(x) = \text{sign}(w \cdot x + b)$$

where,

$f(x)$: Decision function output

w: Weight vector

x: Input vector

b: Bias term

3.1.4. Neural Network Activation Function (e.g., Sigmoid)

$$\sigma(z) = \frac{1}{1 + e^{-z}}$$

where,

$\sigma(z)$: Sigmoid function output

z: Weighted sum of inputs

3.1.5. Backpropagation Update Rule for Weights (Gradient Descent)

$$W_{ij} = W_{ij} - \alpha \frac{\partial E}{\partial W_{ij}}$$

where,

W_{ij} : Weight between neuron i and neuron j

α: Learning rate

$\frac{\partial E}{\partial W_{ij}}$: Partial derivative of the error with respect to the weight.

3.1.6. Bayes' Theorem

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

where,

$P(A|B)$: Probability of event A given event B

$P(B|A)$: Probability of event B given event A

$P(A)$ and $P(B)$: Marginal probabilities of events A and B

3.1.7. K-Means Clustering Objective Function

$$J = \sum_{i=1}^{k} \sum_{j=1}^{n} \left|\left|x_j - \mu_i\right|\right|^2$$

where,

J: Objective function (sum of squared distances)

k: Number of clusters

μ_i: Centroid of cluster i

x_j: Data point j

3.1.8. Gaussian Distribution Probability Density Function

$$f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

where,

$f(x|\mu, \sigma^2)$: Probability density function of the Gaussian distribution

μ: Mean of the distribution

σ^2: Variance of the distribution

3.1.9. ReLU (Rectified Linear Unit) Activation Function

$$f(x) = ma\,x(0, x)$$

where,

$f(x)$: Output of the ReLU activation function

x Input to the activation function

3.1.10. Softmax Function (Multiclass Classification)

$$\text{softmax}(z)_i = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}}$$

where,

$\text{softmax}(z)_i$: Probability of class i in a multiclass classification

e^z : Exponential of the input for class i

$\sum_{j=1}^{K} e^{z_j}$: Sum of exponentials over all classes

3.1.11. Reinforcement Learning - Q-Learning Update Rule

$$Q(s,a) = (1-\alpha)Q(s,a) + \alpha\left(R + \gamma\, max_{a'}\, Q\,(s', a')\right)$$

where,

$Q(s, a)$: Value of state-action pair (s, a)

a: Learning rate

R: Immediate reward

γ:Discount factor

$\max_{a'} Q(s', a')$: Maximum value of the next state-action pair

3.1.12. PCA (Principal Component Analysis) Objective Function

$$J = \frac{1}{m}\sum_{i=1}^{m} \left|\left|x^{(i)} - \bar{x}^{(i)}\right|\right|^2$$

where,

J : Objective function (mean squared reconstruction error)

m : Number of data points

$x^{(i)}$: Original data point

$\bar{x}^{(i)}$: Reconstructed data point

3.1.13. Generative Adversarial Network (GAN) Objective Function

$$[\min_{G}\max_{D} V\,(D,G) = E_{x\sim p_{\text{dt}}(x)}[\log D\,(x)] + E_{z\sim p_z(z)}\left[\log\left(1 - D\left(G(z)\right)\right)\right]]$$

This represents the objective function of a GAN, where G is the generator, D is the discriminator, x are real data samples, and z are random noise samples.

3.1.14. Neural Style Transfer Loss Function

$$[y = f\left(\sum_{i=1}^{n} w_i x_i + b\right)]$$

where,

y is the output.

f is the activation function.

w_i are the weights.

x_i are the inputs.

b is the bias term.

Building Information Modeling (BIM) is a critical aspect of modern architectural design, and AI is playing a pivotal role in advancing its capabilities (Tulubas Gokuc and Arditi, 2017; Donato *et al.*, 2018; Mikhailov *et al.*, 2020; Thuesen *et al.*, 2010). BIM involves creating a digital representation of a building that includes geometric, spatial information, and data about the materials, components, and systems used in construction. AI algorithms can analyze this data to extract valuable insights for decision-making. For instance, AI can identify clashes or conflicts in the design, helping architects and engineers detect and resolve issues before construction begins. The integration of AI in BIM also allows for the automation of routine tasks, such as quantity take-offs and clash detection. Machine learning models can predict material quantities based on historical data, streamlining the cost estimation process. Clash detection algorithms, powered by AI, can identify potential conflicts between different building elements and systems, reducing errors and rework during construction.

In the construction phase, AI continues to enhance efficiency and safety. Robotics and automation powered by AI are increasingly used for tasks such as site surveying, excavation, and bricklaying. Construction robots equipped with AI algorithms can navigate sites, analyze the environment, and execute tasks with precision, accelerating the construction process and reducing the risk of accidents. AI is also contributing to Augmented Reality (AR) in construction. AR applications, integrated with AI, allow architects and construction teams to overlay digital information onto the physical construction site. This includes 3D models, construction schedules, and real-time data, enhancing on-site decision-making by providing a visual representation of the digital model in the physical environment. Furthermore, AI is making significant strides in post-occupancy evaluation and building performance analysis. Building management systems with AI algorithms can monitor and analyze the performance of various building systems, such as HVAC and lighting. Machine learning models can optimize the operation of these systems, improving energy efficiency and occupant comfort. Occupancy sensors and IoT devices, connected to AI platforms, enable real-time monitoring of building usage (Gao and Fan, 2006; Swati and Priyanka, 2010; Shoaib *et al.*, 2012; Singh *et al.*, 2020). AI algorithms can analyze this data to identify patterns of occupancy and usage, aiding architects and building managers in making informed decisions about space utilization and resource allocation. This data-driven approach to post-occupancy evaluation contributes to the creation of more user-centric and sustainable designs.

From the conceptual phase to construction and post-occupancy evaluation, AI algorithms and models are reshaping the way architects approach design challenges. Generative design, parametric design, structural optimization, material selection, and BIM are just a few examples of how AI is enhancing creativity and decision-making in architectural design. As technology advances, the collaboration between human creativity and artificial intelligence promises to redefine possibilities and outcomes in architectural practice. The synergy between the architect's vision and the computational capabilities of AI is not only streamlining the design process but also opening doors to unprecedented levels of ingenuity and sustainability in the built environment. Figure 3 shows the leading-edge technologies for architectural design.

4. Virtual Reality (VR) and Augmented Reality (AR) in Architectural Design

Architectural design has been profoundly reshaped by the transformative influence of Virtual Reality (VR) and Augmented

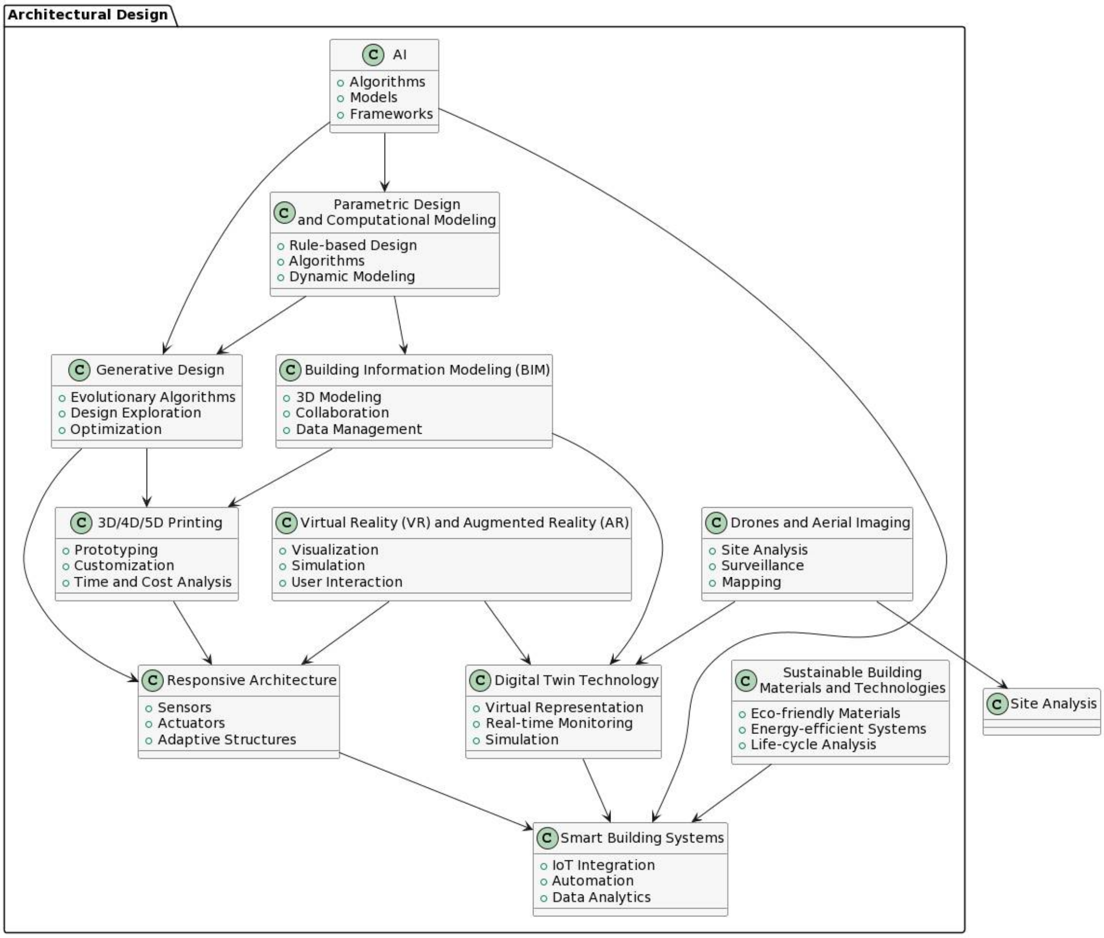

Figure 3: Leading-Edge Technologies for Architectural Design

Reality (AR), introducing groundbreaking tools and experiences that elevate the entire design process (Ergün *et al.*, 2019; Chan, 1997; Frost and Warren, 2000; Shouman *et al.*, 2022; Sørensen, 2013). The ongoing progress of cutting-edge VR and AR technologies is granting architects unprecedented capabilities to visualize, communicate, and perfect their designs. This discussion delves into the diverse applications of VR and AR in architectural design, spotlighting the latest advancements in these technologies.

4.1. Virtual Reality in Architectural Design

VR immerses users in entirely digital environments, empowering architects to fashion realistic three-dimensional representations of their designs (Chan, 1997; Frost and Warren, 2000). State-of-the-art VR technology provides architects with high-resolution headsets and advanced motion tracking, intensifying the immersive experience. Virtual walkthroughs stand out as a primary application, allowing architects and clients to navigate digital spaces, gaining authentic insights into scale, proportion, and spatial relationships.

$$VR_{Arch} + AR_{Arch} = Design_{Immersive}$$

This equation suggests that the combination of Virtual Reality in Architectural design VR_{Arch} and Augmented Reality AR_{Arch} in Architectural design leads to the creation of an immersive design experience $Design_{Immersive}$.

Following equations are fundamental in the design and calibration of virtual and augmented reality systems

4.1.1. Field of View (FOV) Calculation

$$FOV = 2 \cdot \arctan\left(\frac{d}{2f}\right)$$

where,

FOV is the field of view

d is the display size

f is the focal length of the display

4.1.2. Parallax Error in Stereoscopic Displays

$$\text{Parallax Error} = \frac{d^2}{4f}$$

Where,

d is the interocular distance (distance between the eyes)

f is the distance to the object

4.1.3. Stereoscopic Depth Perception

$$\text{Depth} = \frac{B \cdot f}{D}$$

where,

B is the binocular disparity

f is the focal length of the eyes

D is the distance to the object

4.1.4. Lens Distortion Correction

$$r_{\text{corrected}} = r \cdot (1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

Where,

$r_{corrected}$ is the corrected radius

r is the original radius from the center

k_1, k_2, k_3 are distortion coefficients.

4.1.4.1. Design Collaboration

VR facilitates collaborative design processes by enabling architects, clients, and stakeholders to convene in a shared virtual space. Real-time collaboration enhances communication and understanding, irrespective of physical locations. Advanced VR platforms may incorporate features like voice communication, annotation tools, and synchronized design updates, fostering a more efficient and dynamic collaborative workflow.

4.1.4.2. Design Evaluation and Simulation

Architects leverage VR to comprehensively assess designs, simulating lighting conditions, material textures, and environmental factors in virtual environments. This capability enables architects to evaluate the impact of natural light at different times of the day and experiment with materials before finalizing decisions. Experiencing a design in VR helps identify potential issues and refine details for optimal outcomes.

4.1.4.3. Client Presentations

Architectural firms leverage VR as a powerful presentation tool, immersing clients in a virtual representation of proposed designs. This immersive experience enhances client engagement and understanding, enabling more informed decision-making. Leading-edge VR systems may offer realistic rendering capabilities, blurring the line between the virtual and real worlds.

4.2. Augmented Reality in Architectural Design

Augmented Reality overlays digital information onto the real world, equipping architects with context-aware tools that enhance the physical environment. High-quality visualizations and improved interactivity, provided by devices like smart glasses or tablets, broaden the applications of AR in architectural design (Lee *et al.*, 2020; Shouman *et al.*, 2022; Sørensen, 2013).

4.2.1. Site Analysis and Visualization

AR aids architects in on-site analysis and visualization by overlaying digital design models onto physical sites. This helps assess how proposed structures integrate with existing environments, considering factors like topography, surrounding buildings, and infrastructure, facilitating informed decisions about placement and orientation.

4.2.2. Construction Guidance

AR technology guides construction processes by visualizing construction plans overlaid onto physical sites. This ensures accurate placement, adherence to design specifications, and enhances overall efficiency.

4.2.3. Interactive Design Review

AR enables interactive design reviews by superimposing digital models onto physical scale models or printed plans. This dynamic overlay allows architects and clients to explore design options and variations in real-time, fostering engaging and collaborative review processes.

4.2.4. Maintenance and Facility Management

Beyond design and construction, AR finds applications in maintenance and facility management. Digital overlays through AR devices display maintenance instructions, equipment details, or repair information, aiding efficient maintenance and management of built environments.

4.3. Integration of VR and AR

Cutting-edge technologies seamlessly bridge the gap between VR and AR, enabling architects to transition between immersive virtual environments and enhanced real-world experiences. This comprehensive toolkit, combining VR for detailed design exploration and AR for on-site visualization and construction guidance, contributes to a fluid and interconnected architectural design process, fostering creativity, efficiency, and collaboration.

5. Parametric Design and Computational Modeling

Parametric design and computational modeling have brought about a paradigm shift in architectural design, equipping architects with unprecedented tools for conceiving, analyzing, and realizing intricate structures (Gu *et al.*, 2021; Schumacher, 2015; Bhooshan, 2017). These innovative approaches mark a departure from traditional, static design methods towards dynamic, data-driven methodologies.

5.1. Unleashing Creativity Through Form Exploration

Parametric design empowers architects to explore a multitude of design possibilities by defining and manipulating parameters. By establishing relationships between elements, architects can generate intricate and innovative forms that were previously impractical. Tools like Grasshopper for Rhino enable the creation of complex geometries and patterns that dynamically respond to changing parameters, fostering a more creative and exploratory design process.

5.2. Harnessing Generative Design

Computational modeling facilitates generative design, where algorithms produce and evaluate solutions based on predefined criteria. This approach enables architects to generate numerous design alternatives, optimizing factors like structural efficiency and energy performance. Particularly potent in the early project stages, generative design helps architects discover innovative solutions, pushing the boundaries of conventional design thinking.

5.3. Optimizing Performance Through Analysis

Parametric design and computational modeling allow architects to optimize designs for various performance criteria.

Integration of analysis tools into the design process enables assessment of factors like structural stability, thermal performance, and daylighting efficiency. This optimization not only enhances overall functionality but also contributes to sustainable design by minimizing resource consumption and energy usage, facilitating more informed and efficient decision-making.

5.4. Creating Responsive Environments

Parametric design facilitates the creation of responsive and adaptive environments that dynamically adjust to changing conditions. Responsive facades, for example, can adapt to factors such as sunlight, temperature, or user preferences, optimizing comfort and energy efficiency. This capability is especially relevant in smart cities and buildings, where computational models create spaces intelligently responding to user needs and environmental considerations.

5.5. Customization and Personalization

Parametric design allows a high degree of customization in architecture, tailoring designs to meet specific user requirements. This level of customization enhances user experience and satisfaction, as spaces can be finely tuned to address unique occupant needs. Computational design is particularly evident in creating parametrically driven façades, interiors, and furniture.

Table 2: Applications of Parametric Design and Computational Modelling in AD

S. No.	Application	Description	Parametric Design	Computational Modeling	Advantages
1	Generative Design	Utilizes algorithms for creative exploration based on defined parameters	Algorithmic rule sets, input parameters, generative scripts	Parametric representation, automated design exploration	Enhanced creativity, rapid iteration, design space exploration
2	Form Finding	Optimizes complex forms by simulating structural and environmental forces	Parametric geometry, structural analysis algorithms	Finite Element Analysis (FEA), physics-based simulations	Efficient structural forms, integration of performance criteria
3	Responsive Architecture	Creates dynamic, responsive environments using real-time data	Sensor input parameters, real-time data integration	Simulation of environmental conditions, real-time feedback	Adaptive design, sustainability, user-centric environments
4	Energy Performance Analysis	Assesses and optimizes energy performance through simulations	Parametric representation, energy analysis algorithms	Energy simulation software, weather data integration	Energy-efficient design, performance optimization
5	Optimization of Building Systems	Optimizes building systems for efficiency and occupant comfort	Parametric representation, system performance criteria	System performance simulation, optimization algorithms	Improved efficiency, occupant comfort, system performance
6	Digital Fabrication and 3D Printing	Generates intricate geometries for digital fabrication processes	Parametric geometry, fabrication-oriented scripts	Digital fabrication tools, 3D printing algorithms	Customizable fabrication, efficient production
7	Parametric Façade Design	Creates adaptive façade systems for optimal environmental performance	Parametric representation, environmental input parameters	Daylighting and shading simulations, climate data integration	Optimal environmental performance, adaptive building skins

Table 2 (Cont.)

8	Urban Planning and Analysis	Analyzes and simulates urban spaces for functional and sustainable design	Parametric representation, spatial analysis algorithms	Urban simulation models, GIS integration	Informed decision-making, sustainable urban design
9	Biomorphic Design	Creates organic, biomimetic structures inspired by natural forms	Biomimicry-inspired algorithms, parametric representation	Simulation of natural processes, biological principles integration	Sustainable and aesthetically unique designs
10	Collaborative Design Processes	Facilitates real-time collaboration among stakeholders	Parametric collaboration platforms, version control	Real-time collaboration features, cloud-based modeling	Improved communication, iterative design refinement
11	Simulation of Human Behavior	Models and simulates human behavior for optimized spaces	Parametric representation of human behavior, interaction models	Human behavior simulation algorithms, crowd dynamics modeling	User-centric design, safety optimization
12	Material Optimization	Explores and optimizes material usage for sustainability	Parametric material allocation, material performance criteria	Material property simulations, life cycle analysis	Sustainable material use, reduced environmental impact
13	Data-Driven Design	Integrates data analytics for informed decision-making	Parametric integration of data sources, data-driven algorithms	Data analytics, machine learning models	Informed decision-making, personalized design solutions

5.6. Advancing Digital Fabrication and Construction

Computational modeling plays a crucial role in implementing digital fabrication techniques, such as 3D printing and robotic construction. Parametric design tools generate precise digital models translated into fabrication instructions, streamlining construction and allowing for highly complex and customized architectural elements. This has the potential to revolutionize the construction industry by increasing efficiency and reducing waste.

5.7. Fostering Collaboration and Interdisciplinary Integration

Parametric design encourages collaboration among architects, engineers, and stakeholders, providing a common platform for interdisciplinary communication. This collaborative approach enhances the integration of structural, environmental, and technical considerations into the design process, resulting in more holistic and well-informed solutions.

5.8. Immersive Simulation and Virtual Reality

Computational modeling enables detailed simulations and virtual prototypes, enhancing architects' understanding of spatial qualities before construction. Virtual reality technologies, coupled with parametric design, offer immersive experiences, aiding effective communication and decision-making.

5.9. Instrumental in Sustainable Design

Parametric design and computational modeling play a vital role in advancing sustainable architecture. These tools allow architects to analyze and optimize designs for energy efficiency, daylighting, and material usage. Environmental performance simulation throughout the design process contributes to the creation of aesthetically pleasing and environmentally responsible buildings.

5.10. Post-Occupancy Evaluation and Adaptability

Post-construction, parametric design remains integral in post-occupancy evaluation. Data collected from the building's performance feeds back into the parametric model, enabling real-time assessment and ongoing optimization. Additionally, parametric design supports adaptability, allowing buildings to evolve to meet changing user needs or accommodate new functions. Table 2 shows the applications of parametric design and computational modelling in AD.

6. Building Information Modeling (BIM) in Architectural Design

BIM has transformed the landscape of architectural design by providing a comprehensive digital portrayal of both the physical and functional attributes of a building (Dounas *et al.*, 2021; Tulubas Gokuc and Arditi, 2017; Donato *et al.*, 2018; Mikhailov *et al.*, 2020). This collaborative process involves the creation and management of digital models, allowing architects, engineers, and stakeholders to collaborate more efficiently across the entire lifespan of a building. The innovative applications of BIM in architectural design have revolutionized traditional methodologies, elevating the overall design and construction processes. A pivotal application of BIM in architectural design is the development of intricate and precise 3D models. Traditional 2D drawings have limitations in conveying the intricacies of a building's design. BIM empowers architects to construct detailed 3D models, offering a more lifelike and immersive representation of the structure. This fosters improved visualization and comprehension of the design by all involved parties, including clients, builders, and regulatory bodies. These 3D models not only showcase the aesthetic elements but also incorporate vital information about the building's systems, materials, and spatial relationships. BIM promotes a multidisciplinary approach to architectural design, encouraging collaboration among architects, engineers, contractors, and other stakeholders. Through a shared digital platform, team members can contribute to the design process in real-time, reducing the risk of errors and miscommunication. Engineers can seamlessly integrate structural, mechanical, and electrical systems into the BIM model, ensuring cohesive functionality and eliminating clashes during construction.

Moreover, BIM facilitates clash detection and interference analysis, identifying and resolving potential clashes between different building systems before construction begins. This proactive approach minimizes rework and costly changes during construction, contributing to significant time and cost savings. Clash detection is particularly beneficial in complex architectural designs where various systems must seamlessly integrate within the building's structure. The time-saving advantages of BIM extend to the documentation phase of architectural design. BIM software automatically generates detailed and accurate construction documents from the digital model, including plans, sections, elevations, and schedules. Automatic documentation accelerates the design process, reduces the likelihood of errors, and enhances the overall quality and accuracy of construction documents. Additionally, BIM facilitates easy updates to documentation when design changes occur, ensuring stakeholders work with the most current information. BIM's capability to simulate and analyze building performance is another cutting-edge application in architectural design. Architects can utilize BIM for energy analysis, daylighting studies, and thermal performance simulations, enabling the optimization of the building's design for energy efficiency, sustainability, and occupant comfort. Informed decisions based on simulated scenarios lead to environmentally friendly and cost-effective buildings.

BIM also plays a vital role in the construction and facility management phases of a building's lifecycle (Dounas *et al.*, 2021; Tulubas Gokuc and Arditi, 2017; Donato *et al.*, 2018). During construction, the BIM model serves as a central repository for all project information, aiding contractors in construction sequencing, quantity take-offs, and project scheduling (Pan and Zhang, 2023; Abbas *et al.*, 2016;Hardin and McCool, 2015; Huang, 2018; Machado and Vilela, 2020). The detailed information within the BIM model reduces construction errors and facilitates a smoother construction process. In facility management, BIM becomes a valuable asset for building owners and operators, providing information about components, systems, and materials. Such information supports maintenance planning, asset management, and renovations (Rane, 2023a; Rane, 2023b; Moharir *et al.*, 2023; Rane, 2023c; Rane, 2023d; Rane, 2023e). Building owners can access the BIM model to identify specific components, track maintenance schedules, and plan for future modifications or upgrades. The integration of BIM with emerging technologies further enhances its capabilities in architectural design (Thuesen *et al.*, 2010; Kiviniemi and Fischer, 2009; Chang and Shih, 2013). Augmented Reality (AR) and Virtual Reality (VR) applications allow stakeholders to experience the building in a virtual environment before construction.

This immersive experience enhances understanding of spatial relationships, scale, and design aesthetics, enabling real-time design modifications based on stakeholder feedback. The Internet of Things (IoT) and sensor technologies can be integrated with BIM to create "smart buildings." Equipped with sensors collecting real-time data on environmental conditions, energy usage, and occupant behavior, these buildings contribute to improved sustainability and occupant well-being and comfort.

7. Generative Design

Generative design stands as a groundbreaking paradigm in architectural design, harnessing advanced computational algorithms and artificial intelligence to revolutionize the creative process (Di Filippo *et al.,* 2021; Abdelmohsen, 2013; Leitão *et al.,* 2012; Zheng and Yuan, 2021; Veloso and Krishnamurti, 2021; Suphavarophas *et al.,* 2023). Positioned at the forefront of architectural innovation, it fundamentally alters how architects conceptualize, develop, and refine their projects. This progressive approach seamlessly integrates digital technologies, parametric modeling, and machine learning, empowering architects to craft designs that are not only highly efficient but also sustainable and aesthetically captivating (Na, 2021; Gu *et al.,* 2021; Schumacher, 2015). At its essence, generative design involves establishing a set of parameters and constraints, enabling the computer to explore and generate diverse design solutions. This iterative process proves especially potent for intricate architectural challenges, allowing architects to navigate a vast design space, consider multiple variables concurrently, and uncover solutions that may elude traditional design methodologies. Parametric modeling, a pivotal facet of generative design, entails creating a digital model driven by specified parameters or variables. These parameters span functional prerequisites such as spatial utilization and structural integrity to aesthetic considerations like form and visual allure. With a parametric model in place, architects can effortlessly manipulate these variables, facilitating real-time adjustments and immediate feedback on the design's performance. The integration of machine learning enriches generative design by enhancing the system's adaptive capabilities (Wibranek and Tessmann, 2021;Ramsgaard *et al.,* 2020; Yazici, 2020; Ampanavos *et al.,* 2021; Warnett and Zdun, 2022; Meekings and Schnabel, 2017). Machine learning algorithms analyze extensive datasets encompassing architectural precedents, construction methods, and environmental conditions. Through this learning process, the system becomes adept at proposing design solutions that not only exhibit innovation but also draw from historical and contextual knowledge.

7.1. Parametric Equation for a Sine Wave

$$[y(x) = A \cdot \sin(B \cdot x + C) + D]$$

where,

A - represents the amplitude of the sine wave.

B - is the frequency or the number of oscillations within a given range.

C - is the phase shift, determining horizontal displacement.

D - is the vertical shift.

L - System Growth Equation:

$$[F_n = F_{n-1} + F_{n-2}]$$

This equation represents a simple Fibonacci sequence, often used in *L*-systems for generating complex and natural-looking patterns.

7.2. Bezier Curve Equation

$$[P(t) = (1-t)^3 \cdot P_0 + 3(1-t)^2 \cdot t \cdot P_1 + 3(1-t) \cdot t^2 \cdot P_2 + t^3 \cdot P_3]$$

This equation represents a cubic Bezier curve, which is frequently used in computer graphics and parametric design for defining smooth curves.

Generative design emerges as a potent tool in tackling the escalating complexity of architectural challenges, notably in sustainable design and optimizing building performance (Nagy *et al.,* 2017; Agkathidis, 2015; Singh and Gu, 2012; Caldas, 2008). Architects can input sustainability criteria, such as energy efficiency and material usage, allowing the generative design algorithm to explore myriad options to meet these criteria. The outcome is designs that are visually striking while also aligning with environmental consciousness and resource efficiency. Evidence of generative design's impact is apparent in various global architectural projects. For example, in the realm of high-performance facades, generative algorithms analyze environmental data, solar exposure, and thermal conditions to formulate optimized designs enhancing energy efficiency and occupant comfort. Achieving this precision and responsiveness to environmental conditions is a formidable task using traditional design methods. Furthermore, generative design reshapes the concept of form and aesthetics in architecture. Enabling architects to delve into complex geometries and intricate patterns, generative algorithms contribute to the realization of structures once deemed impractical or impossible. The resulting designs often exhibit a seamless blend of form and function, pushing the boundaries of architectural achievement.

A noteworthy advantage of generative design lies in its ability to foster collaboration between architects and machines (Nagy *et al.*, 2017; Agkathidis, 2015; Singh and Gu, 2012). Rather than replacing human creativity, generative design tools serve as collaborative partners, enhancing the architect's creative process. Architects input their design intentions, and the generative algorithm responds with alternative solutions, fostering a dynamic dialogue between human designers and computational tools. The integration of generative design into the architectural workflow holds the potential to streamline the design process, reduce project timelines, and enhance overall project efficiency. By rapidly generating and evaluating design alternatives, architects can make well-informed decisions early in the design phase, yielding superior outcomes in terms of functionality, aesthetics, and sustainability. Despite its immense potential, generative design poses challenges and considerations. Ethical concerns surrounding the impact of automation on the role of architects, as well as issues of accountability and responsibility in the design process, must be addressed. Additionally, the accessibility of generative design tools and the necessity for specialized skills present hurdles to widespread adoption within the architectural community.

8. 3D/4D/5D/6D Printing in Architectural Design

In recent years, the realm of architecture has undergone a substantial metamorphosis, courtesy of advanced manufacturing technologies (Cohen, 2019; Niemelä *et al.*, 2019; Leach and Farahi, 2018; Rane, 2023f; Rane *et al.*, 2023d; Rane *et al.*, 2023e; Rane, 2023g; Rane, 2023h). Notably, 3D printing, along with its subsequent progressions into 4D, 5D, and 6D printing, has emerged as a groundbreaking force in reshaping architectural design and construction.

8.1. 3D Printing in Architecture: A Platform for Creative Innovation

At its essence, 3D printing, or additive manufacturing, involves the layer-by-layer creation of three-dimensional objects from digital models. This process surmounts many constraints associated with conventional manufacturing, empowering architects to conceptualize and materialize intricate designs that were previously deemed impractical or unattainable.

8.2. Architectural Prototyping and Model Construction

A primary application of 3D printing in architecture is rapid prototyping and model construction. Architects can fabricate scaled-down physical models of their designs, fostering a more tangible and immersive comprehension of spatial relationships and design elements. This enhances the design process and facilitates effective communication with clients and stakeholders.

8.3. Elaborate Geometries and Tailored Designs

3D printing facilitates the realization of complex geometries that would be challenging or costly using traditional construction methods. Architects can now design structures with intricate details, unconventional shapes, and customized components, pushing the boundaries of creativity and allowing for a more personalized approach to architectural design.

8.4. 4D Printing: Evolution of Dynamic Architecture Over Time

Building upon the capabilities of 3D printing, 4D printing introduces an additional dimension – time (Campbell *et al.*, 2014; Yi and Kim, 2021; Cheng *et al.*, 2020; Yi, 2022; Demoly *et al.*, 2021; Tibbits, 2014). Objects produced through 4D printing are designed to transform or self-assemble in response to external stimuli, such as heat, water, or light. In architecture, this concept introduces new possibilities for dynamic structures that can adapt to changing conditions.

8.5. Adaptive Building Components

4D printing enables the creation of building components that respond to environmental factors. For example, a facade could adjust its permeability based on temperature or sunlight, optimizing energy efficiency and creating a dynamic aesthetic. This adaptability aligns with the growing emphasis on sustainable and responsive architecture.

8.6. Self-Assembling Structures

The self-assembly capabilities of 4D printing hold immense potential for constructing temporary or emergency shelters. Components could be printed flat, transported easily, and then assemble themselves on-site, mitigating logistical challenges associated with traditional construction methods.

8.7. 5D Printing: Fusion of Intelligence and Data Integration

5D printing takes the integration of technology in architecture a step further by incorporating intelligent features and data connectivity (Titotto, 2021; Ghazal *et al.*, 2023; Chaczko *et al.*, 2019; Sajjad *et al.*, 2023; Ravoor *et al.*, 2021; Monfared *et al.*, 2021). This evolution aligns with the increasing importance of smart cities and buildings, where data-driven decisions contribute to efficiency, sustainability, and user comfort.

8.8. Smart Materials and Embedded Sensors

In 5D printing, smart materials embedded with sensors can create structures that respond to real-time data. For instance, a building's façade could adjust its transparency based on sunlight intensity, or structural elements could monitor and report stress levels. This integration of technology enhances the building's performance and longevity.

8.9. Data-Driven Design and Optimization

Architects can leverage data analytics to optimize designs and make informed decisions throughout the construction process. By integrating information about environmental conditions, user behavior, and energy usage, 5D printing facilitates a holistic approach to architectural design, ensuring structures are not only aesthetically pleasing but also functional and sustainable.

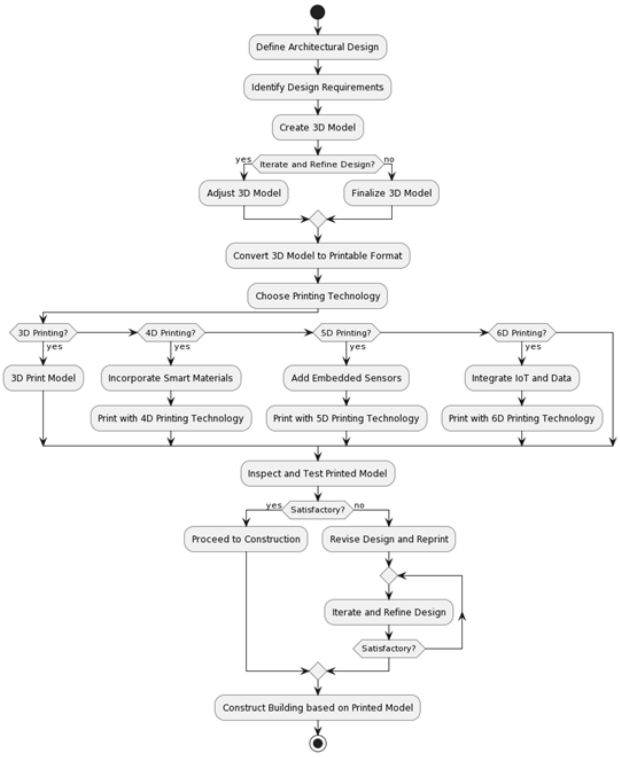

Figure 4:3D/4D/5D/6D Printing in Architectural Design

8.10. 6D Printing: Paving the Way for Self-Sustaining Structures

The concept of 6D printing extends beyond the physical and data-driven aspects, incorporating sustainability and environmental considerations (Amiri *et al.*, 2023; Yu *et al.*, 2023; Vatanparast *et al.*, 2023; Patoliya *et al.*, 2023). Such evolution reflects a paradigm shift towards creating structures that are not only intelligent and responsive but also self-sustaining over the long term (Rane, 2023i; Rane, 2023j; Patil and Rane, 2023; Rane, 2023k; Rane, 2023l).

8.11. Eco-Friendly Materials and Energy Harvesting

6D printing involves the use of eco-friendly materials and the integration of energy harvesting technologies. Buildings can be designed to generate and store their own energy, reducing reliance on external power sources. Additionally, sustainable materials, such as biodegradable polymers, can be utilized in the printing process, minimizing the environmental impact of construction.

8.12. Life Cycle Analysis and Adaptive Design

A crucial aspect of 6D printing is the incorporation of life cycle analysis into the design process. Architects can assess the environmental impact of a structure from its construction to its eventual deconstruction. This approach encourages adaptive design, where buildings can be modified or repurposed over time, extending their lifespan and minimizing waste.

9. Challenges

9.1. Technological Limitations

Despite the exciting possibilities presented by 3D/4D/5D/6D printing, there are technological challenges that must be addressed. These include limitations in printing speed, material variety, and the need for continuous advancements in software and hardware to keep pace with the evolving demands of architectural design.

9.2. Regulatory and Ethical Concerns

The integration of intelligent features and data connectivity raises concerns about privacy, security, and ethical considerations. Architects and policymakers must collaborate to establish clear guidelines for the ethical use of data in smart buildings and ensure that privacy rights are protected.

9.3. Cost Implications

Initially, the cost of 3D/4D/5D/6D printing technologies may be prohibitive for some projects. However, as the technology matures and becomes more widespread, it is expected that costs will decrease, making these innovations more accessible to a broader range of architects and construction projects.

3D/4D/5D/6D printing technologies are revolutionizing the field of architectural design, offering unparalleled possibilities for creativity, sustainability, and efficiency (Yu *et al.*, 2023; Vatanparast *et al.*, 2023; Patoliya *et al.*, 2023). From the foundational capabilities of 3D printing to the dynamic, data-driven, and self-sustaining features of 6D printing, architects now possess a versatile toolkit. While challenges persist, the ongoing development of these technologies holds the promise of reshaping the built environment in ways once only imagined in the realm of science fiction. As architects continue to explore and integrate these printing technologies into their practice, the future of architecture appears to be one where intelligence, adaptability, and sustainability converge to create structures that not only meet the needs of today but also anticipate the challenges of tomorrow.

10. Drones and Aerial Imaging in Architectural Design

In recent years, the fusion of cutting-edge drones and aerial imaging technologies has brought about a paradigm shift in the realm of architectural design. These advanced tools have not only transformed how architects conceive and plan projects but have also left a profound impact on the entire design process, spanning from site analysis to project documentation.

10.1. Site Analysis and Surveying

Drones play a pivotal role in architectural design, particularly in site analysis and surveying (Montanari *et al.*, 2018; Pavelka *et al.*, 2018; Liang and Delahaye, 2019; Kannan and Yadav, 2021; Kays *et al.*, 2019; Dundas *et al.*, 2021; Karaoulis *et al.*, 2022). Traditional land surveying methods, known for their time-consuming nature and limited data comprehensiveness, are being supplanted by cutting-edge drones equipped with high-resolution cameras and LiDAR (Light Detection and Ranging) sensors. These drones provide architects with a swift and accurate means of surveying a site, capturing detailed topographic data, 3D terrain models, and vegetation maps. This wealth of information empowers architects to make informed decisions about site layout, building placement, and overall project feasibility. Real-time data gathering facilitated by drones expedites decision-making during initial site analysis, not only streamlining the design process but also minimizing errors in site understanding. This heightened efficiency results in more precise and effective architectural solutions.

10.2. Design Conceptualization and Visualization

Aerial imaging assumes a critical role in the conceptualization and visualization stages of architectural design. Drones, equipped with high-definition cameras, capture stunning aerial photographs and videos, providing architects with a unique perspective of the site and its surroundings. This bird's-eye view enhances designers' understanding of the contextual relationship between the proposed structure and the environment, encompassing neighboring buildings, landscape features, and natural elements. These visualizations serve as powerful communication tools when presenting design concepts to clients, stakeholders, and regulatory bodies. Aerial imagery improves the comprehensibility of design proposals, facilitating easier grasp by non-professionals and expediting project approval.

10.3. Environmental Impact Assessment

Drones equipped with specialized sensors, such as multispectral and thermal cameras, contribute to a comprehensive environmental impact assessment in architectural design (Bian *et al.*, 2021; Choi *et al.*, 2016; Duan *et al.*, 2019; Bor-Yaliniz *et al.*, 2017; Kim, 2018; Alsamhi *et al.*, 2022). These sensors detect factors like heat distribution, vegetation health, and pollution levels, providing architects with data to evaluate the ecological impact of their designs and ensure compliance with environmental regulations. By utilizing drones for environmental monitoring, architects gain insights into the site's ecological nuances, aiding in informed decision-making regarding material choices, energy consumption, and landscaping strategies. This proactive approach promotes environmentally responsible design and enhances the project's resilience to changing climatic conditions.

10.4. Construction Monitoring and Management

Drones continue to play a pivotal role in architectural projects during the construction phase. Unmanned aerial vehicles conduct regular site inspections, capturing high-resolution images and videos that document construction progress. Real-time monitoring allows architects to identify potential issues, assess work quality, and ensure construction aligns with the design intent. Drones with thermal imaging capabilities prove particularly useful in identifying discrepancies in building materials and detecting potential structural issues. Early detection enhances overall safety and quality, reducing the likelihood of costly rework and delays. Data collected by drones can be integrated into Building Information Modeling (BIM) systems, providing a digital representation of the building's construction history for future maintenance, renovations, and facility management.

10.5. Project Documentation and Marketing

Aerial imaging significantly contributes to project documentation and marketing efforts in architectural design. Drones capture high-quality photographs and videos showcasing completed projects from unique perspectives (Casella *et al.*, 2022; Chen *et al.*, 2021; Molnar, 2018; Cunha *et al.*, 2022; Ryan *et al.*, 2022; Maxwell, 2022). These visuals are instrumental in creating compelling portfolios, marketing materials, and presentations for architects and developers. Additionally, aerial imagery can be leveraged for creating immersive virtual tours and 3D models of architectural projects. This interactive content allows clients and stakeholders to experience the design in a more engaging and realistic manner, fostering a deeper understanding and appreciation for the architectural vision.

10.6. Emergency Response and Risk Assessment

Drones prove invaluable in emergency response and risk assessment for architectural projects. In the event of natural disasters or accidents, drones equipped with cameras and sensors quickly survey affected areas, providing real-time data to assess damage and plan recovery efforts (Chowdhury *et al.*, 2017; Munawar *et al.*, 2022; Hewett and Puangpontip 2022; Muhamat *et al.*, 2022; Restas, 2015; Kucharczyk and Hugenholtz, 2021; Mohd Daud *et al.*, 2022). Such capability is particularly crucial in disaster-prone regions, where traditional assessment methods may be hindered by access limitations or safety concerns (Rane, 2023m; Rane, 2023n; Rane, 2023o; Rane, 2023p; Rane, 2023q). Architects can also use drones for risk assessment during the design and construction phases. Aerial inspections identify potential hazards proactively, enhancing overall project safety.

11. ChatGPT and similar generative AI in Architectural design

OpenAI's formidable language model, ChatGPT, stands as a promising force in reshaping the architectural design landscape. The integration of ChatGPT in architectural design has immense potential to revolutionize the industry. From ideation to documentation, the model's capabilities in natural language understanding, creativity, and problem-solving significantly enhance the efficiency and creativity of architectural processes. As technology advances, architects are poised to embrace these tools to create more innovative, sustainable, and culturally sensitive designs, ushering in a future where human creativity and artificial intelligence coalesce to open new possibilities for architectural design. This section explores numerous applications of ChatGPT in architectural design, aiming to revolutionize creative processes, collaboration methods, and problem-solving approaches.

11.1. Ideation and Conceptualization

In the initial stages of architectural design, ChatGPT proves invaluable by assisting designers in generating innovative ideas and conceptualizing designs. Through dynamic conversations based on criteria like site dimensions, functional requirements, and aesthetic preferences, designers can explore diverse design possibilities, fostering a faster and more intuitive brainstorming process.

11.2. Automated Sketching and Rendering

Traditionally time-consuming tasks, such as manual sketching and rendering of initial design concepts, can be automated by ChatGPT. Verbal descriptions provided by designers can be translated into visual representations, expediting the design phase and enabling architects to iterate more efficiently through quick visual feedback loops.

11.3. Space Planning and Functional Optimization

Efficient space planning, critical for projects with specific functional requirements, can be enhanced by ChatGPT. Analyzing user inputs, the model proposes design solutions that improve functionality, flow, and accessibility. Designers can discuss objectives, and ChatGPT suggests spatial configurations, furniture arrangements, and circulation patterns aligned with project goals.

11.4. Material Selection and Sustainability

In the crucial decision of selecting materials impacting aesthetics and sustainability, ChatGPT aids architects by considering factors like durability, cost, and environmental impact. The model suggests sustainable design strategies, contributing to overall sustainability by recommending the use of renewable materials, energy-efficient systems, and green technologies.

11.5. Design Collaboration and Team Communication

Facilitating seamless communication within diverse teams, ChatGPT serves as a collaborative platform for architects, engineers, and clients. It assists in clarifying design intent, resolving conflicts, and generating documentation. Bridging communication gaps, ChatGPT fosters more inclusive and participatory design processes.

11.6. Generative Design and Parametric Modeling

Integrating with parametric modeling tools, ChatGPT aligns well with generative design processes. Architects can explore a vast design space, considering various parameters and constraints. The model generates design alternatives based on user preferences, leading to more optimized and innovative solutions.

11.7. Design Critique and Feedback

As a virtual design critic, ChatGPT offers insights and suggestions based on design principles and historical precedents. Designers receive feedback on aspects such as proportion, scale, and composition, contributing to the iterative improvement of design concepts.

11.8. Code Compliance and Regulations

Navigating complex building codes and regulations becomes simpler with ChatGPT. It provides information on local building codes, zoning requirements, and accessibility standards, ensuring that designs meet necessary regulatory standards.

11.9. Real-time Design Assistance

Functioning as a real-time design assistant, ChatGPT provides immediate responses to queries and suggestions to overcome challenges, enhancing the agility of the design process.

11.10. Design Documentation and Reports

Streamlining the generation of design documentation and reports, ChatGPT converts verbal descriptions into well-articulated written content. This saves time and ensures effective communication of design intentions to stakeholders.

11.11. VR and AR Integration

Integration with VR and AR technologies allows designers to describe concepts to ChatGPT, which generates virtual environments or augmented overlays. This immersive experience enhances the communication of spatial concepts, fostering a deeper understanding of the design vision.

11.12. Historical and Cultural Context Integration

ChatGPT assists architects in researching and integrating relevant historical and cultural elements into designs. By analyzing textual input and providing contextual information, the model helps create designs sensitive to the cultural and historical identity of the site.

12. Digital Twin Technology

Digital Twin Technology, a cutting-edge concept with diverse applications, has seamlessly integrated into various industries, including architectural design (Park *et al.*, 2020; Ozturk, 2021; Rausch *et al.*, 2020; Dezen-Kempter *et al.*, 2020). This groundbreaking methodology involves crafting a virtual replica or simulation of a physical object, system, or process. In architectural design, Digital Twin Technology is reshaping how architects conceptualize, plan, design, construct, and manage buildings (Ozturk, 2021; Rausch *et al.*, 2020). At its core, Digital Twin Technology constructs a digital counterpart of a physical entity, enabling real-time monitoring, analysis, and simulation. This approach amalgamates technologies such as 3D modeling, Internet of Things (IoT), sensors, data analytics, and artificial intelligence (Vilas-Boas *et al.*, 2023; Emmert-Streib, 2023; Drissi Elbouzidi *et al.*, 2023; Mozo *et al.*, 2022; Huang *et al.*, 2021; Biller and Biller, 2023). The resulting digital twin functions as a dynamic and interactive representation mirroring the real-world object, empowering architects with insights to optimize processes and make informed decisions.

12.1. Architectural Design Precision and Efficiency

During the initial stages of architectural design, Digital Twin Technology streamlines planning by providing architects with a precise and efficient tool. Architects can fashion a digital twin of the proposed structure, allowing visualization and assessment in a virtual environment. This not only elevates the design process but also facilitates early detection of potential issues or areas for improvement. Digital twins aid in constructing detailed 3D models, enabling architects to explore diverse design possibilities and iterate rapidly (Han *et al.*, 2020; Liu *et al.*, 202; Wang *et al.*, 2023; DebRoy *et al.*, 2017). Such technology fosters real-time collaboration among architects, engineers, and stakeholders, fostering creativity, efficient problem-solving, and data-informed decision-making in the design phase (DebRoy*et al.*, 2017; Rane, 2023r; Rane, 2023s; Rane and Attarde, 2016; Rane, 2016; Rane *et al.*, 2017).

12.2. Simulation and Performance Evaluation

A key advantage of Digital Twin Technology in architectural design lies in its capacity to simulate and analyze a building's performance. This encompasses evaluating factors like energy efficiency, thermal comfort, lighting, and structural integrity. By assimilating data from sensors and real-world conditions, architects can predict the building's behavior under various scenarios. For example, simulating sunlight impact at different times of the day enables optimized window placement for natural lighting and reduced heat gain. Such simulations assist in evaluating energy consumption and identifying areas for enhancement. This data-centric approach ensures not only sustainable designs but also contributes to cost savings throughout the building's life cycle.

12.3. Construction and Project Oversight

Digital Twin Technology assumes a pivotal role in the construction phase, offering real-time insights into project progress and performance. Construction sites equipped with sensors and IoT devices continuously gather data on parameters such as material usage, equipment status, and worker activities. This data is then incorporated into the digital twin, creating a comprehensive and dynamic representation of the construction site. Architects and project managers can monitor project status, identify potential issues or delays, and optimize workflows for enhanced efficiency. The technology also facilitates quality control by comparing the as-built structure with the digital twin, ensuring adherence to original design specifications.

12.4. Building Lifecycle Management

The utility of Digital Twin Technology extends beyond construction, encompassing the entire building lifecycle. Architects leverage the digital twin as a central repository for design details, maintenance schedules, and performance data. This information proves invaluable for facility management, enabling proactive maintenance and minimizing downtime. Embedded IoT sensors continuously collect data on factors like temperature, humidity, and occupancy, feeding real-time information into the digital twin. Predictive analytics anticipate maintenance needs, averting costly repairs and ensuring the structure's longevity.

12.5. Enhancing Occupant Experience and Smart Buildings

Digital Twin Technology contributes to the creation of smart buildings that elevate the occupant experience. Integration of IoT devices and sensors enables architects to monitor and optimize factors like indoor air quality, lighting, and temperature. The digital twin serves as a control center, facilitating real-time adjustments based on occupancy and environmental conditions. For instance, if sensors detect underutilized areas, the digital twin optimizes energy consumption by adjusting lighting and HVAC systems. This not only enhances occupant comfort but also promotes energy savings and sustainability.

12.6. Challenges and Future Outlook

While Digital Twin Technology offers myriad benefits, challenges include the integration of diverse technologies, data security concerns, and the need for standardized protocols (Broo and Schooling, 2023; Zheng *et al.*, 2022; Rasheed *et al.*, 2020; Fuller *et al.*, 2020; Botín-Sanabria *et al.*, 2022; Ghita *et al.*, 2020). Nevertheless, the future holds promise with anticipated advancements in artificial intelligence, machine learning, and augmented reality augmenting digital twin capabilities. The development of open standards and increased collaboration among industry stakeholders will play a pivotal role in realizing the full potential of this transformative technology.

13. Smart Building Systems

Smart building systems mark a revolutionary shift in architectural design, ushering in a new era of intelligent, efficient, and sustainable structures. These systems integrate state-of-the-art technologies to elevate the functionality, comfort, and environmental performance of buildings. At the forefront, these multifaceted smart building systems encompass various aspects of design, construction, and operation. At the core of smart building systems lies the integration of advanced sensor technologies. Functioning as a building's sensory organs, these sensors gather data on parameters such as temperature, humidity, occupancy, and air quality. Real-time analysis of this data empowers buildings to dynamically adapt and respond to changing conditions, enhancing occupant comfort and optimizing Heating, Ventilation, and Air Conditioning (HVAC) systems based on actual usage patterns (Eini *et al.*, 2021; Le *et al.*, 2019; Janhunen *et al.*, 2020; Bäcklund *et al.*, 2023; Froufe *et al.*, 2020; Yong *et al.*, 2022). A pivotal element in smart building design is the incorporation of Building Information Modeling (BIM). Going beyond traditional 3D modeling, BIM includes intelligent data representing both the physical and functional characteristics of a building. This digital representation serves as a collaborative platform for architects, engineers, and stakeholders, facilitating efficient decision-making, streamlined communication, and the simulation of various scenarios for optimal design choices.

In the realm of energy efficiency, smart building systems leverage advanced technologies to minimize environmental impact. Energy management systems use real-time data to optimize electricity, heating, and cooling consumption. Machine learning algorithms predict future demand by analyzing historical usage patterns, allowing for proactive adjustments to prevent energy wastage. The integration of renewable energy sources, such as solar panels and wind turbines, further reduces reliance on traditional power grids, promoting sustainability. The advent of the Internet of Things (IoT) has transformed the smart building landscape. IoT connects various devices and systems within a building through a network, enabling seamless communication and automation. Smart sensors, actuators, and devices create an interconnected ecosystem that enhances efficiency and convenience, such as adjusting lighting based on occupancy or integrating security systems with access control for enhanced safety.

Smart buildings prioritize occupant well-being through features like advanced air quality monitoring and natural light optimization (Starace *et al.*, 2022; Zivelonghi and Giuseppi, 2024; Wang *et al.*, 2022; Guyot *et al.*, 2018; Correia *et al.*, 2022). Air quality sensors detect pollutants, triggering ventilation systems for a healthy indoor environment. Automated shading systems maximize natural light while minimizing glare and heat gain, contributing to occupant comfort and energy efficiency. The implementation of smart building systems extends beyond construction, focusing on ongoing building management. Building Management Systems (BMS) or Building Automation Systems (BAS) act as central control hubs, integrating HVAC, lighting, security, and other systems for efficient operation and maintenance. Remote monitoring enables facility managers to access real-time data, make informed decisions, and enhance overall performance.

In the pursuit of sustainability, smart buildings embrace eco-friendly practices like rainwater harvesting, greywater recycling, and green roofs. These practices contribute to water conservation and enhance a building’s resilience to environmental factors. Green building certifications, such as LEED and BREEAM, are increasingly sought after, reflecting a commitment to environmentally responsible design and construction. Artificial Intelligence (AI) is pivotal in the evolution of smart building systems. Machine learning algorithms analyze vast amounts of data to identify patterns and make predictive recommendations. AI-driven predictive maintenance anticipates equipment failures, minimizing downtime and extending the lifespan of building systems. Virtual assistants powered by AI enhance occupant interaction, providing personalized experiences and optimizing energy usage based on individual preferences. The concept of smart cities amplifies the impact of smart building systems. In a smart city ecosystem, interconnected buildings share data with each other and with city infrastructure to optimize resource allocation, traffic flow, and emergency response. Collaborative efforts between buildings, transportation systems, and public services contribute to a more sustainable and livable urban environment. Cybersecurity is a critical consideration in the design and operation of smart building systems. Increased connectivity and reliance on digital technologies elevate the vulnerability to cyber threats. Robust cybersecurity measures, including encryption, secure access controls, and regular software updates, are essential to safeguard sensitive data and ensure the uninterrupted operation of smart building systems.

14. Conclusion

The examination of cutting-edge technologies in architectural design emphasizes the transformative influence of advancements across diverse fields, fostering innovation and reshaping the architectural landscape. The integration of Artificial Intelligence (AI) into architectural design processes emerges as a pivotal development, empowering architects to leverage computational power and data-driven insights for optimizing their creations. AI not only streamlines routine tasks but also contributes to the generation of innovative design solutions, elevating the creative potential of architects. Virtual Reality (VR) and Augmented Reality (AR) emerge as potent tools transcending traditional design methods. These technologies immerse architects and stakeholders in virtual environments, offering an unparalleled spatial understanding and facilitating real-time collaboration. The fusion of VR and AR with architectural design enhances visualization and serves as a communication bridge, ensuring a more holistic and participatory approach to the design process. Parametric Design and Computational Modeling, combined with algorithmic thinking, instigate a paradigm shift in design exploration. The capability to manipulate parameters and generate intricate forms allows architects to push the boundaries of creativity. The synergy between computational tools and design thinking fosters a dynamic design process, enabling architects to iteratively refine their ideas and optimize performance parameters.

Building Information Modeling (BIM) remains a cornerstone in architectural practice, promoting collaboration, data interoperability, and efficient project management. The ability to create a comprehensive digital representation of a building facilitates better decision-making throughout the project lifecycle, from design and construction to operation and maintenance. Sustainable building materials and technologies are gaining prominence, reflecting an increasing awareness of environmental concerns. Integrating eco-friendly materials and energy-efficient technologies into architectural designs is no longer optional but a necessity. The emphasis on sustainability aligns with global efforts to mitigate the environmental impact of the built environment, promoting resilience and resource efficiency. Generative Design, propelled by AI algorithms, transcends conventional design thinking by exploring countless design iterations based on specified parameters. This approach enhances creativity and leads to more optimized and efficient designs. The integration of generative design with other technological trends paves the way for a more intelligent and responsive architectural design process. The introduction of 3D/4D/5D Printing brings novel possibilities in materialization and construction processes. These technologies enable architects to translate intricate digital designs into tangible structures, promoting customization and complexity in architectural forms. The integration of printing technologies with sustainable materials further contributes to the eco-friendly evolution of architectural practice.

Responsive architecture, enabled by sensor technologies and adaptive systems, allows structures to dynamically interact with their environment. This capability fosters buildings that can respond to changing conditions, optimizing energy use and user comfort. The integration of responsive design principles enhances the resilience and efficiency of architectural creations in the face of evolving environmental factors. Drones and aerial imaging revolutionize site analysis, surveying, and monitoring during the design and construction phases. The ability to gather real-time, high-resolution data from the air enhances decision-making processes, improves safety, and contributes to a more accurate representation of the site context. Digital Twin Technology, representing a virtual replica of a physical structure, offers architects a powerful tool for design validation, performance simulation, and ongoing monitoring. The synergy between the digital twin and real-world structures provides valuable insights for optimizing operational efficiency and maintenance strategies. Smart building systems, incorporating Internet of Things (IoT) technologies, empower architects to create intelligent and interconnected structures. These systems enhance user experience, optimize energy consumption, and contribute to the overall sustainability of buildings. The integration of smart technologies not only improves the functionality of architectural designs but also aligns with the growing trend of creating responsive and user-centric environments. As these technologies continue to evolve, architects are poised to explore uncharted realms, pushing the boundaries of what is possible and redefining the very essence of architectural design.

Declarations

Funding

No funding was received.

Conflicts of Interest/Competing Interests

No conflict of interest.

References

Abbas, A., Din, Z.U. and Farooqui, R. (2016). Integration of BIM in Construction Management Education: An Overview of Pakistani Engineering Universities. *Procedia Engineering*, 145, 151-157.

Abdelmohsen, S.M. (2013, November). Reconfiguring Architectural Space Using Generative Design and Digital Fabrication: A Project Based Course. In Proceedings of the 17th Conference of the Iberoamerican Society of Digital Graphics.

Agkathidis, A. (2015). Generative Design Methods. In Proceedings of eCAADe, September, 47-55.

Agkathidis, A. (2016). *Generative Design.* Hachette UK.

Alsamhi, S.H., Shvetsov, A.V., Shvetsova, S.V., Hawbani, A., Guizani, M., Alhartomi, M.A. and Ma, O. (2022). Blockchain-Empowered Security and Energy Efficiency of Drone Swarm Consensus for Environment Exploration. *IEEE Transactions on Green Communications and Networking*, 7(1), 328-338.

Amiri, E., Sanjarnia, P., Sadri, B., Jafarkhani, S. and Khakbiz, M. (2023). Recent Advances and Future Directions of 3D to 6D Printing In Brain Cancer Treatment And Neural Tissue Engineering. *Biomedical Materials.*

Ampanavos, S., Nourbakhsh, M. and Cheng, C.Y. (2021). Structural Design Recommendations in the Early Design Phase Using Machine Learning. In International Conference on Computer-Aided Architectural Design Futures , July, 190-202, Springer Singapore, Singapore.

Azadi, S. and Nourian, P. (2021). A Modular Generative Design Framework for Mass-customization and Optimization in Architectural Design. In 39th eCAADe Conference.

Bäcklund, K., Molinari, M., Lundqvist, P. and Palm, B. (2023). Building Occupants, Their Behavior and the Resulting Impact on Energy Use in Campus Buildings: A Literature Review with Focus on Smart Building Systems. In Energies (Vol. 16, Issue 17). https://doi.org/10.3390/en16176104

Bhawiyuga, A., Kartikasari, D.P., Amron, K., Pratama, O.B. and Habibi, M.W. (2019). Architectural Design of IoT-cloud Computing Integration Platform. TELKOMNIKA (Telecommunication Computing Electronics and Control), 17(3), 1399-1408.

Bhooshan, S. (2017). Parametric Design Thinking: A Case-study of Practice-embedded Architectural Research. *Design Studies*, 52, 115-143.

Bian, H., Tan, Q., Zhong, S. and Zhang, X. (2021). Assessment of UAM and Drone Noise Impact on the Environment Based on Virtual Flights. *Aerospace Science and Technology*, 118, 106996.

Biller, B. and Biller, S. (2023). Implementing Digital Twins That Learn: AI and Simulation Are at the Core. *Machines*, 11(4). https://doi.org/10.3390/machines11040425

Bingol, K., Akan, A. E., Örmecioðlu, H.T. and Er, A. (2020). Artificial Intelligence Applications in Earthquake Resistant Architectural Design: Determination of Irregular Structural Systems with Deep Learning and Image AI Method.

Bor-Yaliniz, I., Szyszkowicz, S.S. and Yanikomeroglu, H. (2017). Environment-aware Drone-base-station Placements In Modern Metropolitans. *IEEE Wireless Communications Letters*, 7(3), 372-375.

Botín-Sanabria, D.M., Mihaita, S., Peimbert-García, R.E., Ramírez-Moreno, M.A., Ramírez-Mendoza, R.A. and Lozoya-Santos, J. de J. (2022). Digital Twin Technology Challenges and Applications: A Comprehensive Review. In *Remote Sensing*, 14(6). https://doi.org/10.3390/rs14061335

Broo, D.G. and Schooling, J. (2023). Digital Twins in Infrastructure: Definitions, Current Practices, Challenges and Strategies. *International Journal of Construction Management*, 23(7). https://doi.org/10.1080/15623599.2021.1966980

Bukar, U.A. and Othman, M. (2022). Architectural Design, Improvement, and Challenges of Distributed Software-defined Wireless Sensor Networks. *Wireless Personal Communications*, 122(3), 2395-2439.

Cabuk, U.C., Tosun, M., Dagdeviren, O. and Ozturk, Y. (2022). An Architectural Design for Autonomous and Networked Drones. In MILCOM 2022-2022 IEEE Military Communications Conference (MILCOM), November, 962-967, *IEEE.*

Caldas, L. (2006). GENE_ARCH: An Evolution-based Generative Design System for Sustainable Architecture. In Workshop of the European Group for Intelligent Computing in Engineering, June, 109-118. Berlin, Heidelberg: Springer Berlin Heidelberg.

Caldas, L. (2008). Generation of Energy-efficient Architecture Solutions Applying GENE_ARCH: An Evolution-based Generative Design System. *Advanced Engineering Informatics*, 22(1), 59-70.

Cámara, J., Silva, M., Garlan, D. and Schmerl, B. (2021). Explaining Architectural Design Tradeoff Spaces: A Machine

Learning Approach. In Software Architecture: 15th European Conference, ECSA 2021, Virtual Event, Sweden, September 13-17, 2021, Proceedings, 49-65, Springer International Publishing.

Campbell, D.A. and Wells, M. (1994). A Critique of Virtual Reality in the Architectural Design Process. University of Washington HITL Technical Report R-94, 3(2).

Campbell, T.A., Tibbits, S. and Garrett, B. (2014). The Next Wave: 4D printing. *Atlantic*, 1-16.

Casella, E., Lewin, P., Ghilardi, M., Rovere, A. and Bejarano, S. (2022). Assessing the Relative Accuracy of Coral Heights Reconstructed from Drones and Structure from Motion Photogrammetry on Coral Reefs. *Coral Reefs*, 41(4). https://doi.org/10.1007/s00338-022-02244-9

Chaczko, Z., Klempous, R., Rozenblit, J., Chiu, C., Kluwak, K. and Smutnicki, C. (2019). Enabling Design of Middleware for Massive Scale IOT-based Systems. In 2019 IEEE 23rd International Conference on Intelligent Engineering Systems (INES), April, 000219-000223. IEEE.

Chan, C.S. (1997). Virtual Reality in Architectural Design. In CAADRIA, 97(April), 1-10.

Chang, Y.F. and Shih, S.G. (2013). BIM-based Computer-aided Architectural Design. *Computer-Aided Design and Applications*, 10(1), 97-109.

Chen, C.J., Huang, Y.Y., Li, Y.S., Chen, Y.C., Chang, C.Y. and Huang, Y.M. (2021). Identification of Fruit Tree Pests with Deep Learning on Embedded Drone to Achieve Accurate Pesticide Spraying, 9. https://doi.org/10.1109/ACCESS.2021.3056082

Cheng, T., Tahouni, Y., Wood, D., Stolz, B., Mülhaupt, R. and Menges, A. (2020). Multifunctional Mesostructures: Design and Material Programming for 4D-printing. In Proceedings of the 5th Annual ACM Symposium on Computational Fabrication, November, 1-10.

Choi, C.H., Jang, H.J., Lim, S.G., Lim, H.C., Cho, S.H. and Gaponov, I. (2016). Automatic Wireless Drone Charging Station Creating Essential Environment for Continuous Drone Operation. In 2016 International Conference on Control, Automation and Information Sciences (ICCAIS), October, 132-136, IEEE.

Chowdhury, S., Emelogu, A., Marufuzzaman, M., Nurre, S.G. and Bian, L. (2017). Drones for Disaster Response and Relief Operations: A Continuous Approximation Model. *International Journal of Production Economics*, 188. https://doi.org/10.1016/j.ijpe.2017.03.024

Cohen, Z. (2019). Speed Limits: The Architectural Design Possibilities of the 3D Printed Corner. In Proceedings of the 107th Annual ACSA Conference Proceedings, Pittsburgh, PA, USA, March, 28-30.

Correia, A., Ferreira, L.M., Coimbra, P., Moura, P. and de Almeida, A. T. (2022). Smart Thermostats for a Campus Microgrid: Demand Control and Improving Air Quality. *Energies*, 15(4). https://doi.org/10.3390/en15041359

Cunha, R.R., Arrabal, C.T., Dantas, M.M. and Bassaneli, H.R. (2022). Laser Scanner and Drone Photogrammetry: A Statistical Comparison Between 3-dimensional Models and Its Impacts on Outdoor Crime Scene Registration. *Forensic Science International*, 330. https://doi.org/10.1016/j.forsciint.2021.111100

D'Amico, A., Bergonzoni, G., Pini, A. and Currà, E. (2020). BIM for healthy buildings: An Integrated Approach of Architectural Design Based on IAQ Prediction. *Sustainability*, 12(24), 10417.

DebRoy, T., Zhang, W., Turner, J. and Babu, S.S. (2017). Building Digital Twins of 3D Printing Machines. *Scripta Materialia*, 135. https://doi.org/10.1016/j.scriptamat.2016.12.005

Demoly, F., Dunn, M.L., Wood, K.L., Qi, H.J. and Andre, J.C. (2021). The Status, Barriers, Challenges, and Future in Design for 4D printing. *Materials & Design*, 212, 110193.

Dezen-Kempter, E.L.O.I.S.A., Mezencio, D.L., Miranda, E.D.M., De Sãi, D.P. and Dias, U.L.I.S.S.E.S. (2020). Towards a Digital Twin for Heritage Interpretation. In RE Anthr. Des. *Age Humans: Proc*. 25th *Int. Conf. Comput. Archit. Des. Res. Asia*, CAADRIA 2020, 2, 183-191.

Di Filippo, A., Lombardi, M., Lorusso, A., Marongiu, F. and Santaniello, D. (2021). Generative Design for Project Optimization (S). In *DMSVIVA*, 110-115.

Donato, V., Lo Turco, M. and Bocconcino, M.M. (2018). BIM-QA/QC in the Architectural Design Process. *Architectural Engineering and Design Management*, 14(3), 239-254.

Dounas, T., Lombardi, D. and Jabi, W. (2021). Framework for Decentralised Architectural Design BIM and Blockchain Integration. *International Journal of Architectural Computing*, 19(2), 157-173.

Drissi Elbouzidi, A., Ait El Cadi, A., Pellerin, R., Lamouri, S., Tobon Valencia, E. and Bélanger, M.J. (2023). The Role of AI in Warehouse Digital Twins: Literature Review. In *Applied Sciences* (Switzerland), 13(11). https://doi.org/10.3390/app13116746

Duan, Z., Li, Y., Wang, J., Zhao, G. and Svanberg, S. (2019). Aquatic eNvironment Monitoring Using a Drone-based Fluorosensor. *Applied Physics* B, 125, 1-8.

Dundas, S J., Vardanega, M., O'Brien, P. and McLeod, S.R. (2021). Quantifying Waterfowl Numbers: Comparison of Drone and Ground-based Survey Methods for Surveying Waterfowl on Artificial Waterbodies. *Drones*, 5(1), 5.

Eber, W. (2020). Potentials of Artificial Intelligence in Construction Management. *Organization, Technology & Management in Construction: An International Journal*, 12(1), 2053-2063.

Eini, R., Linkous, L., Zohrabi, N. and Abdelwahed, S. (2021). Smart Building Management System: Performance Specifications and Design Requirements. *Journal of Building Engineering*, 39. https://doi.org/10.1016/j.jobe.2021.102222

Emmert-Streib, F. (2023). What Is the Role of AI for Digital Twins? *AI*, 4(3). https://doi.org/10.3390/ai4030038

Ergün, O., Akýn, Þ., Dino, Ý. G. and Surer, E. (2019). Architectural Design in Virtual Reality and Mixed Reality Environments: A Comparative Analysis. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), March, 914-915, IEEE.

Frost, P. and Warren, P. (2000). Virtual Reality Used in a Collaborative Architectural Design Process. In 2000 IEEE Conference on Information Visualization. *An International Conference on Computer Visualization and Graphics*, July, 568-573, IEEE.

Froufe, M.M., Chinelli, C.K., Guedes, A.L.A., Haddad, A.N., Hammad, A.W.A. and Soares, C.A.P. (2020). Smart Buildings: Systems and Drivers. *Buildings*, 10(9). https://doi.org/10.3390/buildings10090153

Fuller, A., Fan, Z., Day, C. and Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*, 8. https://doi.org/10.1109/ACCESS.2020.2998358

Gao, R. X. and Fan, Z. (2006). Architectural Design of a Sensory Node Controller for Optimized Energy Utilization In Sensor Networks. *IEEE Transactions on Instrumentation and Measurement*, 55(2), 415-428.

Garcia Alvarado, R. and Jofre Muñoz, J. (2012). The Control of Shape: Origins of Parametric Design in Architecture in Xenakis, Gehry and Grimshaw.

Gautam, V.K., Pande, C.B., Moharir, K.N., Varade, A.M., Rane, N.L., Egbueri, J.C. and Alshehri, F. (2023). Prediction of Sodium Hazard of Irrigation Purpose using Artificial Neural Network Modelling. *Sustainability*, 15(9), 7593. https://doi.org/10.3390/su15097593

Ghazal, A.F., Zhang, M., Mujumdar, A.S. and Ghamry, M. (2023). Progress in 4D/5D/6D Printing of Foods: Applications and R&D Opportunities. *Critical Reviews in Food Science and Nutrition*, 63(25), 7399-7422.

Ghita, M., Siham, B., Hicham, M., Abdelhafid, A. and Laurent, D. (2020). Digital Twins: Development and Implementation Challenges Within Moroccan Context. *SN Applied Sciences*, 2(5). https://doi.org/10.1007/s42452-020-2691-6

Gu, N., Yu, R. and Behbahani, P. A. (2021). Parametric Design: Theoretical Development and Algorithmic Foundation for Design Generation In Architecture. *Handbook of the Mathematics of the Arts and Sciences*, 1361-1383.

Guyot, G., Sherman, M.H. and Walker, I.S. (2018). Smart Ventilation Energy and Indoor Air Quality Performance in Residential Buildings: A Review. In *Energy and Buildings*, 165. https://doi.org/10.1016/j.enbuild.2017.12.051

Han, Z., Li, Y., Yang, M., Yuan, Q., Ba, L. and Xu, E. (2020). Digital Twin-driven 3D Visualization Monitoring and Traceability System for General Parts in Continuous Casting Machine. *Journal of Advanced Mechanical Design, Systems and Manufacturing*, 14(7). https://doi.org/10.1299/jamdsm.2020jamdsm0100

Hardin, B. and McCool, D. (2015). *BIM and Construction Management: Proven Tools, Methods, and Workflows*. John Wiley & Sons.

Hewett, R. and Puangpontip, S. (2022). On Controlling Drones for Disaster Relief. *Procedia Computer Science*, 207. https://doi.org/10.1016/j.procs.2022.09.430

Hölttä, K.M. and Otto, K.N. (2005). Incorporating Design Effort Complexity Measures in Product Architectural Design and Assessment. *Design studies*, 26(5), 463-485.

Howeidy, D.R. and Arafat, Z. (2017). The Impact of Using 3D Printing on Model Making Quality and Cost in the Architectural Design Projects. *International Journal of Applied Engineering Research*, 12(6), 987-994.

Huang, Y. (2018). A Review of Approaches and Challenges of BIM Education in Construction Management. *Journal of Civil Engineering and Architecture*, 12(6), 401-7.

Huang, Z., Shen, Y., Li, J., Fey, M. and Brecher, C. (2021). A Survey on AI-driven Digital Twins in Industry 4.0: Smart Manufacturing and Advanced Robotics. In *Sensors*, 21(19). https://doi.org/10.3390/s21196340

Janhunen, E., Leskinen, N. and Junnila, S. (2020). The Economic Viability of a Progressive Smart Building System With Power Storage. *Sustainability* (Switzerland), 12(15). https://doi.org/10.3390/su12155998

Ji, L.H. (2022). Application and Optimization of Artificial Intelligence Technology in Architectural Design. *Wireless Communications and Mobile Computing*.

Kallioras, N.A. and Lagaros, N.D. (2020). DzAI!: Deep Learning Based Generative Design. *Procedia Manufacturing*, 44, 591-598.

Kannan, R.J. and Yadav, K.P. (2021). Drone Routing Techniques for Surveying in Urban Areas. *Review of International Geographical Education Online*, 11(5).

Karaoulis, M., Ritsema, I., Bremmer, C., De Kleine, M., Oude Essink, G. and Ahlrichs, E. (2022). Drone-Borne Electromagnetic (DR-EM) Surveying in The Netherlands: Lab and Field Validation Results. *Remote Sensing*, 14(21), 5335.

Kays, R., Sheppard, J., Mclean, K., Welch, C., Paunescu, C., Wang, V., ... & Crofoot, M. (2019). Hot Monkey, Cold Reality: Surveying Rainforest Canopy Mammals Using Drone-mounted Thermal Infrared Sensors. *International Journal of Remote Sensing*, 40(2), 407-419.

Kim, N.H. (2018). Development of Atmospheric Environment Information Collection System Using Drone. *Smart Media Journal*, 7(4), 44-51.

Kiviniemi, A. and Fischer, M. (2009). Potential Obstacles to Using BIM in Architectural Design. *Collaborative Construction Information Management*, 36-54.

Kucharczyk, M. and Hugenholtz, C.H. (2021). Remote Sensing of Natural Hazard-related Disasters With Small Drones: Global Trends, Biases, And Research Opportunities. In *Remote Sensing of Environment*, 264. https://doi.org/10.1016/j.rse.2021.112577

Kullmann, K. (2018). The Drone's Eye: Applications and Implications for Landscape Architecture. *Landscape Research*, 43(7), 906-921.

Le, D.N., le Tuan, L. and Dang Tuan, M.N. (2019). Smart-building Management System: An Internet-of-Things (IoT) Application Business Model in Vietnam. *Technological Forecasting and Social Change*, 141. https://doi.org/10.1016/j.techfore.2019.01.002

Leach, N. and Farahi, B. (Eds.). (2018). *3D-Printed Body Architecture*. John Wiley & Sons.

Lee, J. G., Seo, J., Abbas, A. and Choi, M. (2020). End-Users' Augmented Reality Utilization for Architectural Design Review. *Applied Sciences*, 10(15), 5363.

Leitão, A., Santos, L. and Lopes, J. (2012). Programming Languages for Generative Design: A Comparative Study. *International Journal of Architectural Computing*, 10(1), 139-162.

Liang, M. and Delahaye, D. (2019). Drone Fleet Deployment Strategy for Large Scale Agriculture and Forestry Surveying. In 2019 IEEE Intelligent Transportation Systems Conference (ITSC), October, 4495-4500, IEEE.

Lin, G. and Sang, K. (2022). Application of UAV-Based Oblique Photography in Architectural Design: The Case of Mengyuan Resort Hotel in Yunnan, China. In Proceedings of 2021 4th International Conference on Civil Engineering and Architecture, January, 433-442. Singapore: Springer Nature Singapore.

Liu, R., Li, H. and Lv, Z. (2023). Modeling Methods of 3D Model in Digital Twins. In *CMES - Computer Modeling in Engineering and Sciences*, 136(2). https://doi.org/10.32604/cmes.2023.023154

Liu, S., Chang, R., Zuo, J., Webber, R.J., Xiong, F. and Dong, N. (2021). Application of Artificial Neural Networks in Construction Management: Current Status And Future Directions. *Applied Sciences*, 11(20), 9616.

Liu, Z., Sampaio, P., Pishchulov, G., Mehandjiev, N., Cisneros-Cabrera, S., Schirrmann, A., ... and Bnouhanna, N. (2022). The Architectural Design And Implementation of a Digital Platform for Industry 4.0 SME Collaboration. *Computers in Industry*, 138, 103623.

Machado, R. L. and Vilela, C. (2020). Conceptual Framework for Integrating BIM and Augmented Reality in Construction Management. *Journal of Civil Engineering and Management*, 26(1), 83-94.

Maxwell, S.F. (2022). An Investigation into Trevor Paglen's Drones Photographs, Military Targeting, and Looking Slowly. *Journal of War and Culture Studies*, 15(4). https://doi.org/10.1080/17526272.2022.2116186

Meekings, S. and Schnabel, M. A. (2017). Big Data on Individuals in the Architectural Design Process: Combining Individual's Data With the Architects Toolset. *International Journal of Parallel, Emergent and Distributed Systems*, 32(sup1), S66-S72.

Mikhailov, S., Mikhailova, A., Nadyrshine, N. and Nadyrshine, L. (2020). BIM-technologies and digital modeling in educational architectural design. *In IOP Conference Series: Materials Science and Engineering*, 890(1), 012168, IOP Publishing.

Millán, E., Belmonte, M.V., Boned, F.J., Gavilanes, J., Pérez-de-la-Cruz, J.L. and Díaz-López, C. (2022). Using Machine Learning Techniques for Architectural Design Tracking: An Experimental Study of the Design of a Shelter. *Journal of Building Engineering*, 51, 104223.

Milovanovic, J., Moreau, G., Siret, D. and Miguet, F. (2017). Virtual and Augmented Reality in Architectural Design and Education. In 17th International Conference, CAAD Futures, July.

Moharir, K.N., Pande, C.B., Gautam, V.K., Singh, S.K. and Rane, N.L. (2023). Integration of Hydrogeological Data, GIS and AHP Techniques Applied to Delineate Groundwater Potential Zones in Sandstone, Limestone and Shales Rocks of the Damoh District, (MP) Central India. *Environmental Research*, 115832. https://doi.org/10.1016/j.envres.2023.115832

Mohd Daud, S.M.S., Mohd Yusof, M.Y.P., Heo, C.C., Khoo, L.S., Chainchel Singh, M.K., Mahmood, M.S. and Nawawi, H. (2022). Applications of Drone in Disaster Management: A Scoping Review. In *Science and Justice*, 62(1). https://doi.org/10.1016/j.scijus.2021.11.002

Møller, N.L.H. and Bjørn, P. (2016). In Due Time: Decision-Making in Architectural Design of Hospitals. In COOP 2016: Proceedings of the 12th International Conference on the Design of Cooperative Systems, 23-27 May 2016, Trento, Italy, 191-206, Springer International Publishing.

Molnar, A. (2018). 3D Reconstruction of Monuments From Drone Photographs Based on the Spatial Reconstruction of the Photogrammetric Method. *Advances in Science, Technology and Engineering Systems*, 3(6). https://doi.org/10.25046/aj030633

Monedero, J. (2000). Parametric Design: A Review and Some Experiences. *Automation in Construction*, 9(4), 369-377.

Monfared, V., Bakhsheshi-Rad, H.R., Ramakrishna, S., Razzaghi, M. and Berto, F. (2021). A Brief Review on Additive Manufacturing of Polymeric Composites and Nanocomposites. *Micromachines*, 12(6), 704.

Montanari, A., Kringberg, F., Valentini, A., Mascolo, C. and Prorok, A. (2018). Surveying Areas in Developing Regions Through Context Aware Drone Mobility. In Proceedings of the 4th ACM Workshop on Micro Aerial Vehicle Networks, Systems, and Applications, June, 27-32.

Mozo, A., Karamchandani, A., Gómez-Canaval, S., Sanz, M., Moreno, J.I. and Pastor, A. (2022). B5GEMINI: AI-Driven Network Digital Twin. *Sensors*, 22(11). https://doi.org/10.3390/s22114106

Muhamat, A.A., Zulkifli, A.F., Ibrahim, M.A., Sulaiman, S., Subramaniam, G., Mohamad, S. and Suzuki, Y. (2022). Realising the Corporate Social Performance (CSP) of Takaful (Islamic Insurance) Operators through Drone-Assisted Disaster Victim Identification (DVI). *Sustainability* (Switzerland), 14(9). https://doi.org/10.3390/su14095440

Mukkavaara, J. and Sandberg, M. (2020). Architectural Design Exploration Using Generative Design: Framework Development and Case Study of a Residential Block. *Buildings*, 10(11), 201.

Munawar, H.S., Hammad, A.W.A. and Waller, S.T. (2022). Disaster Region Coverage Using Drones: Maximum Area Coverage and Minimum Resource Utilisation. *Drones*, 6(4). https://doi.org/10.3390/drones6040096

Na, S. (2021). Case Analysis and Applicability Review of Parametric Design in Landscape Architectural Design. *Journal of the Korean Institute of Landscape Architecture*, 49(2), 1-16.

Naboni, R., Kunic, A. and Breseghello, L. (2020). Computational Design, Engineering and Manufacturing of a Material-efficient 3D Printed Lattice Structure. *International Journal of Architectural Computing*, 18(4), 404-423.

Nagy, D., Lau, D., Locke, J., Stoddart, J., Villaggi, L., Wang, R., ... and Benjamin, D. (2017). Project Discover: An Application of Generative Design for Architectural Space Planning. In Proceedings of the Symposium on Simulation for Architecture and Urban Design, May, 1-8.

Niemelä, M., Shi, A., Shirowzhan, S., Sepasgozar, S. and Liu, C. (2019). 3D Printing Architectural Freeform Elements: Challenges and Opportunities in Manufacturing for Industry 4.0. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC), May, 1298-1304.

Ostwald, M.J. (2010). Ethics and the Auto-generative Design Process. *Building Research & Information*, 38(4), 390-400.

Ozturk, G.B. (2021). Digital Twin Research in the AECO-FM Industry. *Journal of Building Engineering*, 40, 102730.

Pan, Y. and Zhang, L. (2023). Integrating BIM and AI for Smart Construction Management: Current Status and Future Directions. *Archives of Computational Methods in Engineering*, 30(2), 1081-1110.

Park, K.T., Lee, J., Kim, H.J. and Noh, S.D. (2020). Digital Twin-based Cyber Physical Production System Architectural Framework for Personalized Production. *The International Journal of Advanced Manufacturing Technology*, 106, 1787-1810.

Patil, D.R. and Rane, N.L., (2023) Customer Experience and Satisfaction: Importance of Customer Reviews and Customer Value on Buying Preference. *International Research Journal of Modernization in Engineering Technology and Science*, 5(3), 3437- 3447. https://www.doi.org/10.56726/IRJMETS36460

Patil, G. (2019). Applications of Artificial Intelligence in Construction Management. *International Journal of Research in Engineering*, 32(03), 32-1541.

Patoliya, J., Vala, K., Makwana, M. and Moradiya, P. (2023). Shape Deformation/Transformation in 4D Printed Food: A Review.

Pavelka, K., Šedina, J. and Matoušková, E. (2018). High Resolution Drone Surveying of the Pista Geoglyph in Palpa, Peru. *Geosciences*, 8(12), 479.

Pena, M.L.C., Carballal, A., Rodríguez-Fernández, N., Santos, I. and Romero, J. (2021). Artificial Intelligence Applied to Conceptual Design. A Review of Its Use in Architecture. *Automation in Construction*, 124, 103550.

Penn, A., Mottram, C., Fatah gen. Schieck, A., Wittkämper, M., Störring, M., Romell, O., ... and Aish, F. (2005). Augmented Reality Meeting Table: A Novel Multi-user Interface for Architectural Design. In *Recent Advances In Design and Decision Support Systems in Architecture and Urban Planning*, 213-231, Springer Netherlands.

Penttilä, H. (2007). Early Architectural Design and BIM. In Computer-Aided Architectural Design Futures (CAADFutures) 2007: Proceedings of the 12th International CAADFutures Conference, November, 291-302. Springer Netherlands, Dordrecht.

P³oszaj-Mazurek, M., Ryñska, E. and Grochulska-Salak, M. (2020). Methods to Optimize Carbon Footprint of Buildings in Regenerative Architectural Design With the Use of Machine Learning, Convolutional Neural Network, and *Parametric Design*. *Energies*, 13(20), 5289.

Pylkkänen, R., Werner, D., Bishoyi, A., Weil, D., Scoppola, E., Wagermaier, W., ... and Mohammadi, P. (2023). The Complex Structure of Fomes Fomentarius Represents an Architectural Design for High-performance Ultralightweight Materials. *Science Advances*, 9(8), eade5417.

Rábago, J. and Portuguez-Castro, M. (2023). Use of Drone Photogrammetry as An Innovative, Competency-Based Architecture Teaching Process. *Drones*, 7(3), 187.

Ramsgaard Thomsen, M., Nicholas, P., Tamke, M., Gatz, S., Sinke, Y. and Rossi, G. (2020). Towards Machine Learning for Architectural Fabrication in the Age of Industry 4.0. *International Journal of Architectural Computing*, 18(4), 335-352.

Rane, N.L. (2023). Multidisciplinary Collaboration: Key Players in Successful Implementation of ChatGPT and Similar Generative Artificial Intelligence In Manufacturing, Finance, Retail, Transportation, and Construction Industry. https://doi.org/10.31219/osf.io/npm3d

Rane, N.L. and Attarde, P.M. (2016). Application of Value Engineering in Commercial Building Projects. *International Journal of Latest Trends in Engineering and Technology*, 6(3), 286-291.

Rane, N.L. and Jayaraj, G.K. (2022). Comparison of Multi-influence Factor, Weight of Evidence and Frequency Ratio Techniques to Evaluate Groundwater Potential Zones of Basaltic Aquifer Systems. *Environment, Development and Sustainability*, 24(2), 2315-2344. https://doi.org/10.1007/s10668-021-01535-5

Rane, N.L. (2016). Application of Value Engineering Techniques in Building Construction Projects. *International Journal of Engineering Sciences & Technology*, 5(7).

Rane, N.L., Achari, A., Choudhary, S.P., Mallick, S.K., Pande, C.B., Srivastava, A. and Moharir, K. (2023). A Decision Framework for Potential Dam Site Selection using GIS, MIF and TOPSIS in Ulhas River Basin, India. *Journal of Cleaner Production*, 138890. https://doi.org/10.1016/j.jclepro.2023.138890

Rane, N.L., Achari, A., Hashemizadeh, A., Phalak, S., Pande, C.B., Giduturi, M., Khan M.Y., Tolche A, D., Tamam, N., Abbas, M, and Yadav, K.K. (2023). Identification of Sustainable Urban Settlement Sites Using Interrelationship Based Multi-influencing Factor Technique and GIS. *Geocarto International*, 1-27. https://doi.org/10.1080/10106049.2023.2272670

Rane, N.L., Achari, A., Saha, A., Poddar, I., Rane, J., Pande, C.B. and Roy, R. (2023). An integrated GIS, MIF, and TOPSIS Approach for Appraising Electric Vehicle Charging Station Suitability Zones in Mumbai, India. *Sustainable Cities and Society*, 104717. https://doi.org/10.1016/j.scs.2023.104717

Rane, N.L., Anand, A. and Deepak K. (2023). Evaluating the Selection Criteria of Formwork System (FS) for RCC Building Construction. *International Journal of Engineering Trends and Technology*, 71(3), 197-205. https://doi.org/10.14445/22315381/IJETT-V71I3P220

Rane, N.L., Choudhary, S.P., Giduturi, M., Pande, C.B. (2023). Remote Sensing (RS) and Geographical Information System (GIS) as A Powerful Tool for Agriculture Applications: Efficiency and Capability in Agricultural Crop Management. *International Journal of Innovative Science and Research Technology (IJISRT)*, 8(4), 264-274. https://doi.org/10.5281/zenodo.7845276

Rane, N.L., Choudhary, S.P., Giduturi, M., Pande, C.B. (2023). Efficiency and Capability of Remote Sensing (RS) and Geographic Information Systems (GIS): A Powerful Tool for Sustainable Groundwater Management" , International *Journal of Innovative Science and Research Technology (IJISRT)*, 8(4), 275-285. https://doi.org/10.5281/zenodo.7845366

Rane, N., Lopes, S., Raval, A., Rumao, D. and Thakur, M.P. (2017). Study of Effects of Labour Productivity on Construction Projects. *International Journal of Engineering Sciences and Research Technology*, 6(6), 15-20.

Rane, Nitin (2023a). 3D, 4D, and 5D printing in Architecture, Engineering, and Construction (AEC) Industry: Applications, Challenges, and Future Scope. Available at SSRN: https://ssrn.com/abstract=4609912 or http://dx.doi.org/10.2139/ssrn.4609912

Rane, Nitin (2023b). Chatbot-Enhanced Teaching and Learning: Implementation Strategies, Challenges, and the Role of ChatGPT in Education. Available at SSRN: https://ssrn.com/abstract=4603204 or http://dx.doi.org/10.2139/ssrn.4603204

Rane, Nitin (2023c). ChatGPT and Similar Generative Artificial Intelligence (AI) for Building and Construction Industry: Contribution, Opportunities and Challenges of Large Language Models for Industry 4.0, Industry 5.0, and Society 5.0. Available at SSRN: https://ssrn.com/abstract=4603221 or http://dx.doi.org/10.2139/ssrn.4603221

Rane, Nitin (2023d). ChatGPT and Similar Generative Artificial Intelligence (AI) for Smart Industry: Role, Challenges and Opportunities for Industry 4.0, Industry 5.0 and Society 5.0. Available at SSRN: https://ssrn.com/abstract=4603234 or http://dx.doi.org/10.2139/ssrn.4603234

Rane, Nitin (2023e). Contribution and Challenges of ChatGPT and Similar Generative Artificial Intelligence in Biochemistry, Genetics and Molecular Biology. Available at SSRN: https://ssrn.com/abstract=4603219 or http://dx.doi.org/10.2139/ssrn.4603219

Rane, Nitin (2023f). Contribution of ChatGPT and Other Generative Artificial Intelligence (AI) in Renewable and Sustainable Energy. Available at SSRN: https://ssrn.com/abstract=4597674 or http://dx.doi.org/10.2139/ssrn.4597674

Rane, Nitin (2023g). Enhancing Customer Loyalty through Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Technologies: Improving Customer Satisfaction, Engagement, Relationship, and Experience. Available at SSRN: https://ssrn.com/abstract=4616051 or http://dx.doi.org/10.2139/ssrn.4616051

Rane, Nitin (2023h). Enhancing Mathematical Capabilities through ChatGPT and Similar Generative Artificial Intelligence: Roles and Challenges in Solving Mathematical Problems. Available at SSRN: https://ssrn.com/abstract=4603237 or http://dx.doi.org/10.2139/ssrn.4603237

Rane, Nitin (2023i). Enhancing the Quality of Teaching and Learning through ChatGPT and Similar Large Language Models: Challenges, Future Prospects, and Ethical Considerations in Education. Available at SSRN: https://ssrn.com/abstract=4599104 or http://dx.doi.org/10.2139/ssrn.4599104

Rane, Nitin (2023j). Integrating Building Information Modelling (BIM) and Artificial Intelligence (AI) for Smart Construction Schedule, Cost, Quality, and Safety Management: Challenges and Opportunities. Available at SSRN: https://ssrn.com/abstract=4616055 or http://dx.doi.org/10.2139/ssrn.4616055

Rane, Nitin (2023k). Integrating Leading-Edge Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Technologies for Smart and Sustainable Architecture, Engineering and Construction (AEC) Industry: Challenges and Future Directions. Available at SSRN: https://ssrn.com/abstract=4616049 or http://dx.doi.org/10.2139/ssrn.4616049

Rane, Nitin (2023l). Potential Role and Challenges of ChatGPT and Similar Generative Artificial Intelligence in Architectural Engineering. Available at SSRN: https://ssrn.com/abstract=4607767 or http://dx.doi.org/10.2139/ssrn.4607767

Rane, Nitin (2023m). Role and Challenges of ChatGPT and Similar Generative Artificial Intelligence in Finance and Accounting. Available at SSRN: https://ssrn.com/abstract=4603206 or http://dx.doi.org/10.2139/ssrn.4603206

Rane, Nitin (2023n). Role of ChatGPT and Similar Generative Artificial Intelligence (AI) in Construction Industry. Available at SSRN: https://ssrn.com/abstract=4598258 or http://dx.doi.org/10.2139/ssrn.4598258

Rane, Nitin (2023o). Roles and Challenges of ChatGPT and Similar Generative Artificial Intelligence for Achieving the Sustainable Development Goals (SDGs). Available at SSRN: https://ssrn.com/abstract=4603244 or http://dx.doi.org/10.2139/ssrn.4603244

Rane, Nitin (2023p). Transformers for Medical Image Analysis: Applications, Challenges, and Future Scope. Available at SSRN: https://ssrn.com/abstract=4622241 or http://dx.doi.org/10.2139/ssrn.4622241

Rane, Nitin (2023q). Transformers in Industry 4.0, Industry 5.0, and Society 5.0: Roles and Challenges. Available at SSRN: https://ssrn.com/abstract=4609915 or http://dx.doi.org/10.2139/ssrn.4609915

Rane, Nitin (2023r). Transformers in Intelligent Architecture, Engineering, and Construction (AEC) Industry: Applications, Challenges, and Future Scope. Available at SSRN: https://ssrn.com/abstract=4609914 or http://dx.doi.org/10.2139/ssrn.4609914

Rane, Nitin (2023s). Transformers in Material Science: Roles, Challenges, and Future Scope. Available at SSRN: https://ssrn.com/abstract=4609920 or http://dx.doi.org/10.2139/ssrn.4609920

Rasheed, A., San, O. and Kvamsdal, T. (2020). Digital Twin: Values, Challenges and Enablers from a Modeling Perspective. *IEEE Access*, 8. https://doi.org/10.1109/ACCESS.2020.2970143

Rausch, C., Sanchez, B., Esfahani, M. E. and Haas, C. (2020). Computational Algorithms for Digital Twin Support in Construction. In Construction Research Congress 2020, March, 191-200, American Society of Civil Engineers, Reston, VA.

Ravoor, J., Thangavel, M. and Elsen S, R. (2021). Comprehensive Review on Design and Manufacturing of Bio-scaffolds For Bone Reconstruction. *ACS Applied Bio Materials*, 4(12), 8129-8158.

Restas, A. (2015). Drone Applications for Supporting Disaster Management. *World Journal of Engineering and Technology*, 03(03). https://doi.org/10.4236/wjet.2015.33c047

Ryan, K.P., Ferguson, S.H., Koski, W.R., Young, B.G., Roth, J.D. and Watt, C.A. (2022). Use of Drones for the Creation and Development of a Photographic Identification Catalogue for an Endangered Whale Population. *Arctic Science*, 8(4). https://doi.org/10.1139/as-2021-0047

Sajjad, R., Chauhdary, S.T., Anwar, M.T., Zahid, A., Khosa, A.A., Imran, M. and Sajjad, M.H. (2023). A Review of 4D Printing-Technologies, Shape Shifting, Smart Materials, and Biomedical Applications. *Advanced Industrial and Engineering Polymer Research.*

Schumacher, P. (2015). Design Parameters to Parametric Design. *The Routledge Companion for Architecture Design and Practice: Established and Emerging Trends*, 3-20.

Shoaib, M., Jha, N.K. and Verma, N. (2012). Algorithm-Driven Architectural Design Space Exploration of Domain-specific Medical-sensor Processors. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 21(10), 1849-1862.

Shouman, B., Othman, A.A.E. and Marzouk, M. (2022). Enhancing Users Involvement in Architectural Design Using Mobile Augmented Reality. *Engineering, Construction and Architectural Management*, 29(6), 2514-2534.

Singh, A.P., Luhach, A.K., Gao, X.Z., Kumar, S. and Roy, D.S. (2020). Evolution of Wireless Sensor Network Design From Technology Centric to User Centric: An Architectural Perspective. *International Journal of Distributed Sensor Networks*, 16(8), 1550147720949138.

Singh, V. and Gu, N. (2012). Towards an Integrated Generative Design Framework. *Design Studies*, 33(2), 185-207.

Sørensen, S.S. (2013). The Development of Augmented Reality as a Tool in Architectural and Urban Design. *NA*, 19(4).

Starace, G., Tiwari, A., Colangelo, G. and Massaro, A. (2022). Advanced Data Systems for Energy Consumption Optimization and Air Quality Control in Smart Public Buildings Using a Versatile Open Source Approach. *Electronics* (Switzerland), 11(23). https://doi.org/10.3390/electronics11233904

Suphavarophas, P., Keonil, N. and Bunyarittikit, S. (2023). Generative Design Process for Alternative Creation of Architectural Design: Application of Willis Tower Shading Analysis Case Study. In IOP Conference Series: Earth and Environmental Science, 1217(1), 012016. IOP Publishing.

Swati, A. J. and Priyanka, R. (2010). Wireless Sensor Network (WSN): Architectural Design Issues and Challenges. *Int. J. Comput. Sci. Eng*, 2(9), 3089-3094.

Talbott, K. (2006). 3D Print as Corporeal Design Medium. *International Journal of Architectural Computing*, 4(4), 137-151.

Tamke, M., Nicholas, P. and Zwierzycki, M. (2018). Machine Learning for Architectural Design: Practices and Infrastructure. *International Journal of Architectural Computing*, 16(2), 123-143.

Thuesen, N., Kirkegaard, P.H. and Jensen, R.L. (2010). Evalution of BIM and Ecotect for Conceptual Architectural Design Analysis. In Computing in Civil and Building Engineering, Proceedings of the International Conference: 30 June-2 July, University of Nottingham, Nottingham, UK.

Tibbits, S. (2014). 4D Printing: Multi Material Shape Change. *Architectural Design*, 84(1), 116-121.

Titotto, S. (2021). From Sketches and Installations to Bioinspired 5D Printing Models: Representation Interactions for Smart Cities. In *Handbook of Research on Developing Smart Cities Based on Digital Twins*, 365-387, IGI Global.

Tjebane, M.M., Musonda, I., Okoro, C. and Onososen, A. (2022). Artificial Intelligence (AI) in Sustainable Construction Management: A Scientometric Review. In Construction in 5D: Deconstruction, Digitalization, Disruption, Disaster, Development: Proceedings of the 15th Built Environment Conference, June, 137-150, Springer International Publishing, Cham.

Tulubas Gokuc, Y. and Arditi, D. (2017). Adoption of BIM in architectural design firms. *Architectural Science Review*, 60(6), 483-492.

Vatanparast, S., Boschetto, A., Bottini, L. and Gaudenzi, P. (2023). New Trends in 4D Printing: A Critical Review. *Applied Sciences*, 13(13), 7744.

Veerappan, C.S. and Keong, P.L.K. (2022, August). A Cross-platform Smart Drone Controller Framework–For Real-time Surveillance and Inspection. In *Journal of Physics: Conference Series*, 2336(1), 012009, IOP Publishing.

Veerappan, C.S., Loh, P.K.K. and Chennattu, R.J. (2022). Smart Drone Controller Framework—Toward an Internet of Drones. *AI and IoT for Smart City Applications*, 1-14.

Veloso, P. and Krishnamurti, R. (2021). Mapping Generative Models For Architectural Design. The Routledge Companion to Artificial Intelligence in Architecture. *Abington, Oxon*, 29-58.

Vilas-Boas, J.L., Rodrigues, J.J.P.C. and Alberti, A.M. (2023). Convergence of Distributed Ledger Technologies with Digital Twins, IoT, and AI for fresh food logistics: Challenges and opportunities. *In Journal of Industrial Information Integration*, 31. https://doi.org/10.1016/j.jii.2022.100393

Wang, H. and Hu, Y. (2022). Artificial Intelligence Technology Based on Deep Learning in Building Construction Management System Modeling. *Advances in Multimedia*, 2022.

Wang, Y., Aslani, F., Dyskin, A. and Pasternak, E. (2023). Digital Twin Applications in 3D Concrete Printing. In *Sustainability* (Switzerland), 15(3). https://doi.org/10.3390/su15032124

Wang, Y., Cooper, E., Tahmasebi, F., Taylor, J., Stamp, S., Symonds, P., Burman, E. and Mumovic, D. (2022). Improving Indoor Air Quality and Occupant Health Through Smart Control of Windows and Portable Air Purifiers in Residential Buildings. *Building Services Engineering Research and Technology*, 43(5). https://doi.org/10.1177/01436244221099482

Warnett, S.J. and Zdun, U. (2022). Architectural Design Decisions for Machine Learning Deployment. In 2022 IEEE 19th International Conference on Software Architecture (ICSA), March, 90-100, IEEE.

Weber, R.E., Mueller, C. and Reinhart, C. (2022). Automated Floorplan Generation in Architectural Design: A Review of Methods and Applications. *Automation in Construction*, 140, 104385.

Wibranek, B. and Tessmann, O. (2021). Interfacing Architecture and Artificial Intelligence: Machine Learning for Architectural Design and Fabrication. In *The Routledge Companion to Artificial Intelligence in Architecture*, 380-393. Routledge.

Xu, H., Chang, R., Pan, M., Li, H., Liu, S., Webber, R. J., ... and Dong, N. (2022). Application of Artificial Neural Networks in Construction Management: A Scientometric Review. *Buildings*, 12(7), 952.

Yazici, S. (2020). A Machine-learning Model Driven by Geometry, Material and Structural Performance Data in Architectural Design Process. In Proceedings of the 38th eCAADe Conference, Berlin, Germany, September, 16-18.

Ye, Z., Jingyu, L. and Hongwei, Y. (2022). A Digital Twin-based Human-robot Collaborative System for the Assembly of Complex-shaped Architectures. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 09544054221110960.

Yi, H. (2022). 4D-printed Parametric Façade in Architecture: Prototyping A Self-shaping Skin Using Programmable Two-way Shape Memory Composite (TWSMC). *Engineering, Construction and Architectural Management*, 29(10), 4132-4152.

Yi, H. and Kim, Y. (2021). Prototyping of 4D-printed Self-shaping Building Skin in Architecture: Design, Fabrication, And Investigation of a Two-way Shape Memory Composite (TWSMC) Façade Panel. *Journal of Building Engineering*, 43, 103076.

Yong, L.C., Aziz, N.M. and Mohd-Rahim, F.A. (2022). Adapting to a New Normal During Covid-19: Leveraging the Smart Building System With BIM Integration for Lifecycle Sustainability. *Planning Malaysia*, 20(4). https://doi.org/10.21837/pm.v20i24.1198

Yoshimura, Y., Cai, B., Wang, Z. and Ratti, C. (2019). Deep Learning Architect: Classification for Architectural Design Through the Eye of Artificial Intelligence. *Computational Urban Planning and Management for Smart Cities*, 16, 249-265.

Yu, Q., Zhang, M., Bhandari, B. and Li, J. (2023). Future Perspective of Additive Manufacturing of Food For Children. *Trends in Food Science & Technology*.

Zandi, Y., Issakhov, A., Roco Videla, Á., Wakil, K., Wang, Q., Cao, Y., ... and Qian, X. (2021). A Review Study of Application of Artificial Intelligence in Construction Management and Composite Beams.

Zhang, L., Pan, Y., Wu, X. and Skibniewski, M.J. (2021). *Artificial Intelligence in Construction Engineering and Management*, 95-124, Springer, Singapore.

Zhang, Y., Meina, A., Lin, X., Zhang, K. and Xu, Z. (2021). Digital Twin In Computational Design and Robotic Construction of Wooden Architecture. *Advances in Civil Engineering*, 1-14.

Zhang, Z., Fort, J.M. and Mateu, L.G. (2023). Exploringthe Potential of Artificial Intelligence as a Tool for Architectural Design: A Perception Study Using Gaudí'sWorks. *Buildings*, 13(7), 1863.

Zheng, H. and Yuan, P.F. (2021). A Generative Architectural and Urban Design Method Through Artificial Neural Networks. *Building and Environment*, 205, 108178.

Zheng, X., Lu, J. and Kiritsis, D. (2022). The Emergence of Cognitive Digital Twin: Vision, Challenges and Opportunities. *International Journal of Production Research*, 60(24). https://doi.org/10.1080/00207543.2021.2014591

Zhou, W., Nair, D., Gunawan, O., van Kessel, T. and Hamann, H.F. (2015, October). A testing platform for on-drone computation. In 2015 33rd IEEE International Conference on Computer Design (ICCD), 732-735, IEEE.

Zivelonghi, A. and Giuseppi, A. (2024). Smart Healthy Schools: An IoT-enabled Concept for Multi-room Dynamic Air Quality Control. *Internet of Things and Cyber-Physical Systems*, 4. https://doi.org/10.1016/j.iotcps.2023.05.005

Žujoviæ, M., Obradoviæ, R., Rakonjac, I. and Miloševiæ, J. (2022). 3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review. *Buildings*, 12(9), 1319.

Cite this article as: Nitin Liladhar Rane, Saurabh P. Choudhary and Jayesh Rane (2023). Leading-Edge Technologies for Architectural Design: A Comprehensive Review. *International Journal of Architecture and Planning*, 3(2), 12-48. doi: 10.51483/IJARP.3.2.2023.12-48.