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# 4D/5D/6D printing technology in the Architecture, Engineering, and Construction (AEC) industry: applications, challenges, and future advancements

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## ABSTRACT

The convergence of 4D, 5D, and 6D printing technologies with the Architecture, Engineering, and Construction (AEC) sector has ushered in an era of unparalleled innovation and efficiency. This study delves into the diverse applications, obstacles, and forthcoming advancements of these cutting-edge printing technologies within the AEC industry. 4D printing, marked by materials that can self-transform or assemble over time, has revolutionized architectural design by enabling dynamic structures that respond to environmental stimuli. 5D printing seamlessly integrates cost estimation into the fabrication process, ensuring real-time project budgeting and management. Additionally, 6D printing incorporates environmental and sustainability data, providing architects and engineers with insights into the long-term environmental impact of their designs. These applications collectively enhance the AEC industry's capacity to create structures that are sustainable, cost-effective, and adaptable. Despite the promising applications, challenges persist. Material constraints, scalability of production, and the need for standardized processes present significant obstacles. Furthermore, integrating intricate data streams for 5D and 6D printing demands robust computational algorithms and efficient data management systems. Ethical concerns surrounding intellectual property, data security, and environmental impact also require careful consideration. To surmount these challenges, ongoing research focuses on advancing material science, innovative fabrication techniques, and the development of intelligent algorithms. Collaboration among interdisciplinary teams, including architects, engineers, computer scientists, and environmental experts, is crucial to unlocking the full potential of these technologies. Additionally, the integration of artificial intelligence and machine learning algorithms holds the promise of streamlining the design process, optimizing material usage, and enhancing predictive modeling. This approach paves the way for a more sustainable and efficient AEC industry. Embracing these advancements is essential for the AEC sector to navigate the complexities of modern architecture, ensuring a sustainable and resilient built environment for future generations.

## KEYWORDS

4D printing; 5D printing; 6D printing' Artificial Intelligence; Construction industry; Structural engineering; Building information modelling

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## Introduction

In the constantly evolving landscape of the Architecture, Engineering, and Construction (AEC) industry, technological advancements have consistently played a central role in shaping how we conceive, design, and build the built environment [1-3]. The fusion of cutting-edge technologies with traditional construction methods has led to innovative solutions that enhance efficiency and expand architectural and engineering possibilities [4-8]. Among these groundbreaking advancements, 4D, 5D, and 6D printing technologies have emerged as transformative tools, revolutionizing the AEC industry by giving materials and structures dynamic capabilities once considered unimaginable [9-14]. Traditionally, the AEC industry relied on conventional construction methods, characterized by rigid structures and static designs. However, with the advent of additive manufacturing techniques, the industry experienced a profound shift. 3D printing, the precursor to 4D, 5D, and 6D printing, introduced the concept of layer-by-layer construction, enabling architects and engineers to create intricate designs with unparalleled precision. Building upon this foundation, 4D, 5D, and 6D printing technologies have expanded construction possibilities by introducing the dimensions of time, cost, and data management [10,12-13].

At its core, 4D printing refers to the process of 3D printing objects that can change their shapes or properties over time in response to external stimuli like heat, light, or moisture [9,10]. This dynamic aspect adds a temporal dimension to traditional 3D printing, allowing structures to self-assemble or adapt to changing environmental conditions. Building on the concept of 4D printing, 5D printing incorporates cost-related information into the design and construction process, enabling real-time cost estimation and budget analysis for efficient resource allocation throughout the project's life [11,12]. Going further, 6D printing incorporates data management and building lifecycle information, enabling the creation of intelligent, data-driven structures that can be monitored, analyzed, and optimized over their entire lifecycle [13,14].

The integration of 4D, 5D, and 6D printing technologies

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has ushered in a new era of architectural and engineering marvels [15-19]. In architecture, dynamic facades responding to weather conditions, self-assembling temporary shelters, and adaptive interior spaces are just a few examples of the innovative applications of 4D printing. In engineering, self-repairing bridges, morphing structures responding to seismic activities, and smart infrastructure adapting to traffic patterns exemplify the transformative potential of these technologies. Additionally, the incorporation of cost and data management in 5D and 6D printing has streamlined project workflows, ensuring efficient resource utilization and enhancing project sustainability. Figure 1 shows the co-occurrence analysis of the keywords in literature.

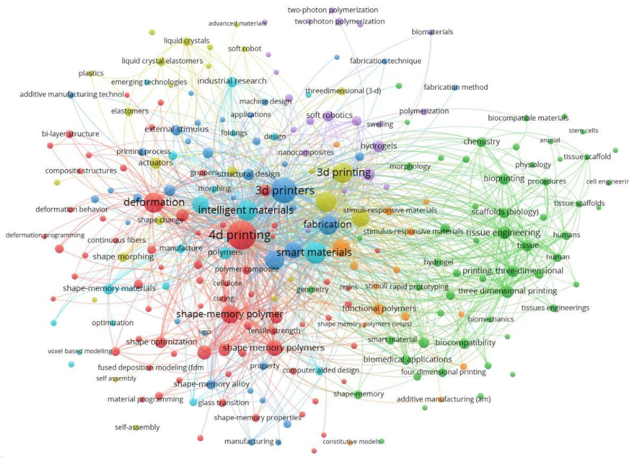


**Figure 1.** Co-occurrence analysis of the keywords in literature.

While the promise of 4D, 5D, and 6D printing technologies is exciting, several challenges and limitations must be addressed to fully realize their potential in the AEC industry [20-27]. Material limitations, such as the availability of suitable materials for dynamic printing, pose a significant hurdle. Additionally, integrating cost and data management requires sophisticated software solutions and standardized protocols, necessitating collaboration among technology developers, architects, engineers, and stakeholders. Ethical considerations related to data privacy, intellectual property, and environmental impact must be carefully navigated to ensure responsible and sustainable implementation of these technologies [28-32]. Despite the challenges, the future of 4D, 5D, and 6D printing in the AEC industry holds immense promise. Continued research and development efforts are crucial to overcoming current limitations and expanding the scope of these technologies. Advances in material science, computational modeling, and artificial intelligence are expected to drive innovation, leading to dynamic structures that not only respond to their environment but also contribute to a more sustainable and resilient built environment [6-9]. As researchers, engineers, and architects collaborate to unlock the full potential of 4D, 5D, and 6D printing technologies, the AEC industry stands on the brink of a transformative era, where the lines between imagination and reality blur, giving rise to structures that are not merely built but are living, adaptive entities shaping the future of our cities and communities. Figure 2 shows the difference between 3D, 4D, 5D, and 6D Printing in the AEC Industry.

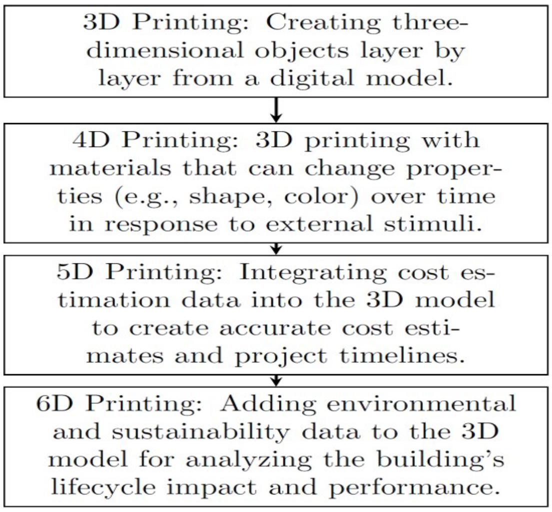


**Figure 2.** Differentiating 3D, 4D, 5D, and 6D Printing in the AEC Industry.

## Methodology

In this research paper, we delved into the world of 4D/5D/6D printing technology within the Architecture, Engineering, and Construction (AEC) industry, with a particular focus on its applications, challenges, and future developments. The methodology adopted for this study primarily encompasses an extensive and all-encompassing review of the existing literature. The primary aim of this literature review is to amass, synthesize, and critically assess the current body of knowledge, research discoveries, and expert viewpoints pertaining to 4D, 5D, and 6D printing technology as applied in the context of the industry. The literature review procedure entailed systematic exploration across a range of academic databases, including but not limited to Google Scholar, IEEE Xplore, ScienceDirect, and ResearchGate. Our search queries incorporated combinations of keywords such as "4D printing," "5D printing," "6D printing," "architecture," "engineering," "construction," "AEC industry," "applications," "challenges," and "future advancements." The search had no temporal restrictions, ensuring a comprehensive coverage of pertinent studies spanning from the inception of these technologies to the present day. Studies that did not have a direct bearing on the AEC sector, or those that did not offer substantial insights into the applications and challenges of 4D, 5D, or 6D printing, were excluded from the review. Comparative analyses were carried out to pinpoint patterns, trends, and gaps in the existing research. The findings of this study, rooted in the critical analysis of existing knowledge, offer valuable insights for researchers, practitioners, and policymakers interested in the integration of these innovative printing technologies in the AEC sector.

## Results and Discussion

### Applications of 4D printing in AEC industry

The Architecture, Engineering, and Construction (AEC) industry is undergoing rapid transformation due to technological advancements, and among these innovations, 4D printing stands out as a revolutionary concept that could redefine the way we approach building design, construction,



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and operation [9,10]. 4D printing, an extension of 3D printing, adds an extra dimension - time - to the process [33-37]. This technology enables 3D-printed objects to change their shape, function, or properties over time in response to external stimuli like temperature, humidity, light, or water. In the realm of the AEC industry, 4D printing holds immense potential, offering solutions to various challenges and facilitating the creation of adaptable, intelligent, and sustainable structures.

**Self-assembling structures**

One of the most promising applications of 4D printing in the AEC industry is the development of self-assembling structures. Unlike traditional construction methods that are labor-intensive and time-consuming, 4D printing allows for the creation of components capable of autonomously assembling themselves with minimal human intervention. These components, embedded with smart materials, can respond to environmental conditions and transform into the desired structure independently. For instance, in disaster-stricken areas, self-assembling shelters can be rapidly deployed, providing immediate relief to those affected. Moreover, these structures significantly reduce construction time and labor costs, making them an attractive option for various construction projects.

## Responsive façades and building envelopes

4D printing enables the fabrication of responsive façades and building envelopes that can adapt to changing environmental conditions. Façade components incorporating smart materials can react to sunlight, temperature, or wind, adjusting the building's permeability, insulation, and shading properties accordingly. This responsiveness enhances energy efficiency by minimizing heat gain, optimizing natural lighting, and reducing the reliance on mechanical systems. Additionally, these adaptive façades improve occupant comfort and well-being, fostering a dynamic relationship between the

**Table 1.** Applications, challenges, and future advancements of 4D Printing in AEC Industry.

| S/N. | Aspect | Applications | Challenges | Future Advancements |
|---|---|---|---|---|
| 1 | Materials | Self-assembling structures<br>- Adaptive facades Smart construction materials<br>- Shape-memory components<br>- Programmable Metamaterials | Limited printable materials<br>Material durability and stability<br>- Cost constraints | Development of advanced materials<br>Biodegradable and sustainable options<br>- Integration of nanotechnology for enhanced properties |
| 2 | Design & Modeling | Complex geometric structures<br>Customizable components<br>- Responsive designs Programmable & reconfigurable designs<br>- Bio-inspired architectures | - Software limitations<br>- Design complexity<br>- Integration challenges | - Enhanced design software<br>- AI-driven design optimization<br>- Bioinformatics for bio- inspired solutions |
| 3 | Construction | Self-assembling infrastructure<br>On-site assembly automation<br>- Rapid prototyping<br>Disaster-responsive structures<br>Customizable construction | - Limited construction techniques<br>- Skill training gaps<br>- Integration hurdles | - Specialized construction techniques<br>- Robotics for automation<br>- Standardized construction protocols<br>- On-demand 4D printing services |
| 4 | Sustainability | - Reduced material waste<br>- Energy-efficient structures<br>- Reconfigurable buildings<br>- Pollution-absorbing structures<br>- Water-responsive architecture | - Environmental impact<br>- Energy consumption<br>- Recycling challenges | - Eco-friendly 4D printing materials<br>- Energy-efficient printing techniques<br>- Water-based & biodegradable solutions<br>- Recycling innovations |
| 5 | Cost & Time | Faster construction timelines<br>- Reduced labor costs<br>- Minimized errors-Customizable & on-demand construction<br>- Streamlined supply chain | - Initial technology investment<br>- R&D costs<br>- Time-consuming processes | - Economical 4D printing technologies<br>- Cost-effective materials & supplychain management<br>- Faster R&D cycles<br>- On-demand printing services |
| 6 | Functionality | - Responsive structures Programmable components<br>- Real-timeresponsiveness<br>- Wearable & bio-integrated architecture<br>- Interactive installations | - Limited long-term stability understanding-Precision challenges<br>- Sensor integration | - Long-term stability studies-Enhanced precision & accuracy<br>- IoT integration for real-time monitoring<br>- Bio-sensing technologies |
| 7 | Regulatory | - Customizable & compliant structures<br>- Disaster-resistant designs<br>- Heritage preservation<br>- Urban planning solutions | - Lack of standardized regulations<br>- Safety certifications<br>- Legal concerns | - Collaboration for standard guidelines<br>- Safety certifications for materials<br>- Legal frameworks for liability issues<br>- Integration of 4D printing in urban planning policies |



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building and its surroundings. Table 1 shows the applications, challenges, and future advancements of 4D Printing in AEC Industry.

### Customizable interior design and furniture

In the realm of interior design and furniture, 4D printing offers new possibilities for customization and flexibility. Architects and designers can create furniture pieces, room dividers, or wall panels that can transform their shapes or functionalities based on users' preferences or specific needs. For instance, a multifunctional table could adjust its height or configuration, accommodating various activities or spatial requirements. This level of customization not only enhances user experience but also reduces waste by eliminating the need for mass-produced, one-size- fits-all furniture items.

### Adaptive infrastructure

4D printing has the potential to transform infrastructure projects by introducing adaptability and resilience. Infrastructure elements such as bridges, dams, or pipelines can be constructed using 4D-printed components that respond to environmental factors like seismic activity or flooding. These adaptive structures can withstand varying stress levels and adjust their shapes or supports to prevent damage or collapse. By integrating sensors and actuators into the infrastructure, real-time data can be collected and analyzed, allowing for predictive maintenance and ensuring the longevity and safety of critical infrastructure assets.

### Smart construction materials

A significant impact area for 4D printing lies in the development of smart construction materials. By embedding sensors, actuators, or microprocessors into construction materials like concrete, steel, or polymers, these materials can exhibit responsive behavior. For instance, 4D-printed concrete can self-heal cracks by releasing repairing agents when damage is detected, enhancing the durability and longevity of structures. Additionally, smart materials can monitor structural integrity, detect faults, and trigger self-repair mechanisms, thereby reducing maintenance costs and increasing the overall safety of buildings and infrastructure.

### Temporary structures and disaster relief

4D printing technology can be instrumental in the rapid deployment of temporary structures during emergencies or disaster relief efforts. These structures can be designed to unfold, assemble, or inflate themselves when exposed to specific environmental conditions, providing immediate shelter, medical facilities, or storage spaces in crisis- stricken areas. Moreover, the lightweight and portable nature of 4D-printed temporary structures allows for easy transportation and quick setup, ensuring timely assistance to affected communities.

### Sustainable construction practices

Sustainability is a central concern in the modern construction industry, and 4D printing offers innovative solutions to enhance sustainable construction practices. By utilizing biodegradable and eco-friendly materials in 4D printing processes, the industry can reduce its environmental impact and minimize waste generation. Additionally, the adaptability and efficiency of 4D-printed structures contribute to resource optimization, as buildings can respond to changing environmental conditions, ensuring optimal energy and water usage. This approach aligns with the principles of sustainable architecture and promotes the development of eco-conscious communities.

**Enhancing construction site safety and monitoring:**

Utilizing 4D printing technology can significantly improve construction site safety by incorporating sensors and actuators into smart safety equipment like hard hats and vests. These embedded devices provide real-time data on workers' vital signs, fatigue levels, and environmental conditions, enabling timely alerts to both workers and supervisors about potential hazards. Moreover, 4D-printed sensors can be integrated into the construction site itself, monitoring structural integrity, material stress, and environmental factors. This innovation facilitates predictive maintenance and early detection of issues, ensuring a safer working environment.

**Customized structural components:**

4D printing enables the creation of customized structural components designed specifically for unique architectural concepts and engineering needs. It eliminates the limitations of traditional manufacturing methods, allowing for the precise 4D printing of intricate trusses, columns, facades, and other complex geometries. These bespoke components not only enhance the aesthetic appeal of buildings but also optimize material usage, minimize waste, and enhance structural performance. Architects and engineers can explore innovative designs that were previously challenging to achieve with conventional construction techniques.

**Adaptive insulation and climate control:**

Engineered 4D-printed materials respond dynamically to environmental conditions, offering adaptable insulation and climate control within buildings. For instance, thermal insulation materials can adjust their properties based on temperature, ensuring comfort in varying weather conditions. Similarly, 4D-printed shading devices can change angles and positions to regulate natural light entry, optimizing daylighting and reducing reliance on artificial lighting. This adaptability enhances energy efficiency, reduces HVAC costs, and promotes sustainable building practices.

**Integrated mechanical, electrical, and plumbing (MEP) systems:**

4D printing technology facilitates the creation of integrated MEP components, combining multiple functions within a single 4D-printed unit. Examples include ductwork embedded with sensors and airflow-controlling mechanisms for ventilation adjustments based on occupancy and air quality. Additionally, 4D-printed electrical conduits can incorporate smart wiring systems for real-time power consumption monitoring and energy distribution optimization. Integrating MEP systems into 4D-printed components streamlines construction processes, reduces installation time, and simplifies maintenance due to self-monitoring capabilities.

**On-demand construction solutions:**

4D printing revolutionizes the construction process by enabling



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on-demand construction of temporary or permanent structures. Construction components can be 4D-printed off-site and transported to the location, where they self-assemble or transform into the desired configuration. This approach significantly reduces construction time, labor costs, and environmental impact associated with traditional methods. On-demand 4D printing is particularly valuable for rapid deployment in emergency situations, such as disaster relief efforts, providing immediate shelter and infrastructure solutions.

**Augmented Reality (AR) integration in construction:**

Combining 4D printing with augmented reality (AR) technology offers innovative solutions for construction visualization, planning, and execution. AR applications overlay digital information onto physical construction elements, enabling real-time visualization for architects, engineers, and construction workers. Integrating 4D- printed components into AR simulations allows stakeholders to observe how these elements transform and interact with the environment over time. This immersive experience enhances collaboration, decision-making, and project communication, ensuring a clear understanding of the project's evolution and the impact of 4D printing on the final outcome.

### Educational and research purposes

4D printing serves as a valuable educational tool, enabling students, researchers, and professionals to explore and understand the intricacies of responsive materials and structures. Educational institutions and research organizations can use 4D printing technology to conduct experiments, develop prototypes, and study the behaviour of smart materials in various environmental conditions. This hands-on approach enhances learning experiences, fosters innovation, and cultivates a new generation of architects and engineers equipped with the knowledge and skills needed to shape the future of the AEC industry.

## Applications of 5D Printing in AEC Industry

The Architecture, Engineering, and Construction (AEC) industry has experienced remarkable technological advancements, leading to more efficient and eco-friendly construction methods [38-43]. One groundbreaking innovation in this realm is 5D printing, a fusion of 3D printing with time and cost management principles [44- 48]. Also referred to as 5D building printing or 5D construction printing, this technology integrates the spatial aspects of 3D printing with time and cost dimensions. Such technology offering a revolutionary approach to effective practices [47,49-54]. Table 2 shows the applications, challenges, and future advancement of 5D Printing in AEC Industry

### Rapid prototyping and design iterations

Traditional prototyping methods in the AEC sector are both time-consuming and expensive. 5D printing empowers architects and engineers to swiftly create detailed physical prototypes. By factoring in time and cost considerations during the design phase, professionals can evaluate multiple design iterations within a shorter timeframe. This accelerates decision-making, allowing architects to experiment with intricate and innovative designs, fostering the creation of more imaginative and practical structures.

### Customized and complex architectural elements

5D printing technology enables the fabrication of intricate and tailor-made architectural components that are otherwise challenging to produce using conventional methods. Architects can craft elaborate facades, ornate decorative elements, and complex patterns, paving the way for a higher level of architectural creativity and uniqueness in building designs. This customization potential unlocks new avenues for innovative and aesthetically pleasing structures.

### Sustainable building practices

Sustainability is a pivotal consideration in modern construction. 5D printing offers the advantage of utilizing eco-friendly and recyclable materials in the printing process. Moreover, the technology enables precise material usage, minimizing waste. By integrating time and cost data, construction projects can be optimized for efficiency, reducing the overall environmental impact. 5D printing supports the AEC industry's endeavors toward sustainable construction practices, contributing to a greener built environment.

### On-site construction and repairs

5D printing can be deployed for on-site construction and repair tasks. Portable 5D printers can be transported to construction sites, facilitating on-demand fabrication of building components. This flexibility is particularly valuable in remote or disaster-affected areas where traditional construction methods may be impractical. Additionally, 5D printing can expedite repairs and replacements, minimizing downtime and reducing costs associated with maintenance and refurbishment projects.

### Affordable housing solutions

The global challenge of affordable housing can significantly benefit from 5D printing technology. By incorporating time and cost considerations, 5D printing allows for the construction of affordable housing units in a cost-effective and time-efficient manner. Mass production of standardized building components becomes achievable, reducing labor costs and construction time. This approach addresses the housing needs of low-income populations, making housing more accessible and affordable.

### Complex geometries and structural innovations

5D printing technology empowers the construction of buildings with intricate geometries and innovative structural designs. Traditional construction methods often face limitations when dealing with complex shapes and structures. 5D printing overcomes these constraints, enabling architects and engineers to explore novel architectural forms and structural solutions. This design freedom opens avenues for iconic landmarks, bridges, and other structures that challenge conventional architectural norms.

### Retrofitting and historical preservation

Preserving historical buildings and retrofitting existing structures for modern functionalities can be challenging. 5D printing offers a solution by enabling the creation of customized components that seamlessly integrate with historical architectures. Architects and conservationists can leverage 5D printing technology to replicate intricate details and decorative elements, ensuring the preservation of cultural heritage.



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**Table 2.** Applications, challenges, and future advancement of 5D Printing in AEC Industry.

| S/N. | Aspect | Applications | Challenges | Future Advancements |
|---|---|---|---|---|
| 1 | Design and Planning | - Rapid prototyping and iteration<br>- Complex geometries and structures<br>- Customization and personalization of designs | - Limited material options<br>- High initial costs<br>- Design complexity challenges | - Development of cost- effective, high-quality materials<br>- Enhanced design software and tools<br>- Integration with advanced BIM systems |
| 2 | Construction | - On-site construction automation<br>- Precise and intricate architectural elements<br>- Reduction in construction waste and time | - Limited size and scale of 3D printers<br>- Ensuring structural integrity and strength of printed components<br>- Workforce skill gaps | - Large-scale 5D printers tailored for construction<br>- Advanced, robust materials for enhanced durability<br>- Specialized training programs for professionals |
| 3 | Cost Estimation | - Accurate cost estimations through real-time data<br>- Improved project budgeting and financial planning<br>- Variance analysis and cost control | - Integration challenges with existing cost estimation software<br>- Data accuracy concerns<br>- Initial setup costs and ROI uncertainties | - Development of specialized cost estimation software for 5D printing projects<br>- Enhanced data analytics and AI-driven cost prediction<br>- Reduced setup costs through technological innovations |
| 4 | -Project Management | Real-time project tracking and monitoring Enhanced communication among stakeholders Streamlined project scheduling and resource allocation | - Data security and privacy considerations<br>- Compatibility issues with existing project management tools<br>- Resistance to technological adoption | - Secure and encrypted communication platforms<br>- Seamless integration with popular project management software<br>- Demonstrated ROI through industry case studies |
| 5 | Sustainability | - Reduced construction waste and material usage<br>- Lower carbon footprint – Sustainable material options | - Recycling and disposal of 3D printed waste<br>- Energy consumption of 5D printing process | - Development of eco- friendly 5D printing materials<br>- Energy-efficient 5D printing technologies<br>- Advanced tools for comprehensive lifecycle |

Moreover, the incorporation of time and cost data facilitates efficient planning and execution of retrofitting projects, minimizing disruptions to historical sites and optimizing resource utilization.

## Digital twins and Building Information Modeling (BIM)

5D printing seamlessly aligns with the concept of Digital Twins and Building Information Modeling (BIM). Digital Twins are digital replicas of physical objects or systems, while BIM involves creating detailed digital representations of building components and systems. By integrating 5D printing with BIM, construction projects can be visualized and simulated in a virtual environment. This integration enables accurate cost estimations, project scheduling, and resource allocation, enhancing overall project management efficiency. Construction professionals can analyze various construction scenarios, identify potential issues, and optimize project parameters before actual construction commences, leading to more informed decision-making and streamlined project execution.

## Educational and research advancements

5D printing serves as a valuable educational tool for students and researchers in the AEC field. It allows aspiring architects and engineers to explore innovative construction techniques and experiment with advanced design concepts. Educational institutions can incorporate 5D printing into their curricula, providing hands-on experience to students and fostering creativity and technical skills. Additionally, researchers can utilize 5D printing technology to study construction materials, structural behaviour, and other aspects related to the AEC industry. This facilitates research and development activities, leading to continuous advancements in construction technology and practices.

**Prototyping and structural components:**

5D printing technology revolutionizes the field of structural engineering by enabling rapid prototyping of intricate components. Engineers can swiftly create detailed prototypes, allowing for efficient testing and analysis of various designs. By factoring in time and cost considerations, engineers can explore multiple design iterations within shorter timeframes, leading to optimized and cost-effective structural solutions.

**Complex and customized structures:**

Structural engineering often demands the creation of intricate and customized designs tailored to specific architectural needs. 5D printing facilitates the construction of complex and unconventional structural elements, challenging to produce using traditional methods. Engineers can fabricate intricate geometries like lattice structures and lightweight trusses, ensuring structural integrity while minimizing material usage. This customization proves invaluable for unique projects such



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as bridges, towers, and unconventional buildings.

**Prefabrication of structural components:**

Prefabrication stands as a cornerstone trend in the construction industry, emphasizing efficiency and cost- effectiveness. 5D printing enables the precise prefabrication of structural components, ensuring accurate dimensions and specifications. These elements can be easily transported and assembled on-site, reducing construction time and labor costs. Integration of time and cost data further optimizes the manufacturing process, guaranteeing timely delivery to construction sites.

**Structural health monitoring with embedded sensors:**

Utilizing 5D printing technology, engineers can embed sensors and monitoring devices directly into structural components during the printing process. These embedded sensors provide real-time structural health monitoring, enabling assessment of structural integrity, load-bearing capacity, and deformation. Incorporating sensors into 5D printed structures allows engineers to collect valuable data for structural analysis and predictive maintenance, ensuring the safety and durability of buildings and infrastructure.

**Lightweight, high-strength structures:**

5D printing empowers engineers to experiment with advanced materials and composite structures, leading to the development of lightweight yet incredibly strong components. By optimizing internal geometries and material compositions, engineers can create structurally efficient components offering superior strength-to-weight ratios. Lightweight structures are especially vital in applications like aerospace engineering, where weight reduction is critical for fuel efficiency and overall performance.

**Disaster-resistant structures:**

In disaster-prone regions, constructing resilient and disaster-resistant structures is paramount. 5D printing technology facilitates the creation of innovative designs and materials that enhance resistance to natural disasters such as earthquakes and hurricanes. Engineers can design components capable of dissipating energy and withstanding extreme forces, ensuring the safety of inhabitants during disasters. Additionally, 5D printing enables rapid on-site construction of emergency shelters and disaster relief structures, offering timely support to affected communities.

**Rehabilitation and retrofitting solutions:**

5D printing plays a pivotal role in rehabilitating and retrofitting existing structures. Engineers can design and fabricate customized structural elements that seamlessly integrate with the original building while addressing structural deficiencies. By factoring in time and cost considerations, engineers can plan the rehabilitation process efficiently, minimizing disruptions to occupants and optimizing resource utilization. 5D printing technology enables the creation of retrofitting solutions that enhance the structural integrity and functionality of aging buildings.

## Applications of 6D Printing in AEC Industry

The field of Architecture, Engineering, and Construction (AEC) has borne witness to remarkable technological advancements over the years [5,7,8]. Among the most promising innovations of recent times is 6D printing, an extension of 3D printing technology [55-62]. 6D printing extends beyond the conventional three dimensions of length, width, and height, incorporating additional dimensions: material properties, time, and functionality [57,60]. This multi-dimensional approach has unveiled a plethora of possibilities for the AEC industry, fundamentally transforming the way buildings and infrastructures are conceived, constructed, and maintained. Table 3 shows the applications, challenges, and future advancements of 6D Printing in AEC Industry.

### Swift prototyping and iterative design

6D printing empowers architects and engineers to craft intricate prototypes with enhanced material properties. This capability expedites rapid prototyping, allowing architects to swiftly manifest their ideas in tangible forms. Iterative design processes, prevalent in the AEC field, reap significant benefits from 6D printing. Architects and designers can produce multiple prototypes with diverse parameters, such as material composition and structural integrity, resulting in optimized designs. This iterative approach expedites the design phase, ultimately curtailing project timelines and expenses.

### Tailored customization

6D printing unveils unprecedented customization and personalization avenues in construction. Architects and designers can forge unique, tailor-made solutions for their clients, incorporating intricate details and complex geometries that were previously challenging to achieve. From facade elements to interior decor, 6D printing empowers the production of highly customized components, elevating the aesthetic appeal of buildings and spaces. This level of personalization not only satiates client preferences but also elevates the overall design quality.

### Sustainable construction

Sustainability stands as a paramount concern in the AEC sector [63-70]. 6D printing contributes significantly to sustainable construction practices. By employing eco-friendly and recyclable materials, 6D printing minimizes environmental impact. Furthermore, the technology allows for precise material utilization, diminishing waste. The ability to print with sustainable materials, such as biodegradable plastics and recycled composites, promotes environmentally conscious construction practices. Additionally, 6D printing facilitates the creation of energy- efficient structures by incorporating intricate designs for natural ventilation and daylight optimization, lessening the reliance on artificial lighting and climate control systems.

### Elaborate architectural elements

6D printing enables the fabrication of complex architectural elements that were previously arduous or expensive to produce. Intricate facade details, ornate columns, and decorative motifs can be manufactured with precision, enhancing the visual allure of buildings. Moreover, 6D printing allows architects to experiment with unconventional shapes and structures, pushing the boundaries of architectural design. This newfound freedom of design expression yields iconic and innovative buildings that captivate the public and redefine urban landscapes.



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**Table 3.** Applications, challenges, and future advancements of 6D Printing in AEC Industry.

| S/N. | Aspect | Applications | Challenges | Future Advancements |
|---|---|---|---|---|
| 1 | Design and Planning | • Creation of intricate architectural prototypes and models. | • Limited availability of suitable 6D printing materials. | • Development of advanced, specialized 6D printing materials. |
| | | • Production of customized, complex structural elements. | • Challenges in optimizing and handling complex designs. | • Enhanced design software for seamless integration. |
| | | • Visualization of building layouts in virtual environments | • High initial costs of 6D printing technology. | • Cost-effective 6D printers for wider accessibility. |
| 2 | Construction | • On-site 3D printing of building components and structures. | • Integration and automation complexities at construction sites. | • Advancements in on-site 6D printing robots and automation systems. |
| | | • Rapid construction of temporary shelters in disaster-stricken areas. | • Concerns about structural integrity and safety. | • Techniques ensuring structural stability and safety. |
| | | • Customized solutions for architecturally complex projects | • Scalability issues for large-scale projects. | • Scalable and efficient 6D printing methods for large constructions |
| 3 | Operation and Maintenance | • Real-time structural health monitoring using 6D printed sensors. | • Challenges in sensor calibration and accuracy. | • Development of highly durable 6D printing materials. |
| | | • Tailored replacement parts for building maintenance. | • Durability and longevity concerns for 6D printed components. | • Integration with IoT technology for seamless monitoring. |
| | | • Smart building components with enbedded sensors for energy efficiency | • Compatibility issues with existing building systems. | • Standardization of 6D printing processes for improved compatibility. |
| 4 | Sustainability | • Use of eco-friendly, sustainable materials for 6D printing. | • Limited availability of environmentally friendly 6D printing materials. | • Research and development of biodegradable and recyclable 6D printing materials |
| | | • Reduced construction waste due to precise material usage. | • Energy consumption during the printing process. | • Energy-efficient 6D printing technologies. |
| | | • Implementation of energy-efficient construction processes | • Recycling and disposal challenges for 6D printed waste | • Implementation of effective recycling |

## On-site construction and repairs

Conventionally, construction components are manufactured in factories and transported to the construction site. 6D printing, however, allows for on-site fabrication of construction elements. Portable 6D printers can be deployed directly to the construction site, reducing transportation costs and logistical complexities. This capability is particularly invaluable in remote or disaster-affected areas where transporting prefabricated components proves challenging. Additionally, 6D printing streamlines on-site repairs and maintenance. Construction teams can swiftly print replacement parts or repair damaged elements, minimizing downtime and ensuring the longevity of structures.

## Structural innovations and optimization

Structural integrity remains paramount in construction, and 6D printing revolutionizes the way structural components are designed and optimized. Engineers can leverage advanced algorithms and simulations to create optimized structures that are both sturdy and lightweight. Complex lattice structures and honeycomb patterns, achievable through 6D printing, offer excellent strength-to-weight ratios, enhancing the structural efficiency of buildings. Furthermore, 6D printing allows for the integration of sensors and actuators directly into structural elements, creating smart structures capable of monitoring their own health and responding to external stimuli. These innovations pave the way for the development of intelligent, self-adaptive buildings that can withstand various environmental conditions and loads.

## Preservation of cultural heritage

Preserving historical and cultural heritage presents a significant challenge for the AEC industry. 6D printing technology plays a pivotal role in the restoration and preservation of historical monuments and artifacts. By digitally scanning and recreating intricate details, damaged or eroded parts of historical structures can be accurately replicated using 6D printing. This process ensures the authenticity and integrity of the restored elements, preserving the cultural significance of heritage sites.



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Additionally, 6D printing enables the creation of museum-quality replicas, allowing visitors to experience historical artifacts in a tactile manner while preserving the originals.

### Cost efficiency and scalability

6D printing provides cost-effective solutions for construction projects. By eliminating the need for expensive molds and tooling, 6D printing substantially reduces initial setup costs. Moreover, the ability to print complex components as a single piece, rather than assembling multiple parts, cuts down on labor costs and assembly time. Scalability is another advantage of 6D printing. Whether it's a small-scale architectural model or a large-scale building component, 6D printers can be tailored to meet various project requirements. This flexibility allows architects and contractors to undertake projects of diverse scales and complexities, maximizing efficiency and profitability.
Disaster response and humanitarian aid
In the aftermath of natural disasters or humanitarian crises, prompt and efficient construction is essential for providing shelter and basic amenities to affected populations. 6D printing technology can be deployed in disaster- stricken areas to quickly fabricate temporary shelters, emergency housing, and infrastructure components. Portable 6D printers, capable of using locally sourced materials, enable rapid on-site construction, addressing the urgent housing needs of displaced communities. Furthermore, 6D printing facilitates the production of essential items such as water filtration systems, medical equipment, and sanitation facilities, enhancing the overall disaster response efforts.

### Education and research

6D printing has a profound impact on architectural education and research. Educational institutions can incorporate 6D printing technology into their curricula, providing students with hands-on experience in advanced manufacturing techniques. This exposure equips future architects and engineers with valuable skills and prepares them for the evolving demands of the industry. Additionally, researchers can explore innovative applications of 6D printing, pushing the boundaries of what is possible in construction. Collaborations between academia and industry can lead to groundbreaking discoveries and novel approaches to design and construction, fostering continuous innovation in the AEC sector.

## Challenges in Implementing 4D/5D/6D Printing Technology

The Architecture, Engineering, and Construction (AEC) sector is currently experiencing a significant transformation as it integrates advanced technologies such as 4D, 5D, and 6D printing [9,11,13]. These cutting- edge methods hold the potential to revolutionize the entire process of designing, constructing, and managing buildings. 4D printing involves the use of materials that can change their properties over time, while 5D printing integrates cost estimation into the design phase, and 6D printing incorporates sustainability and lifecycle analysis [10,12,14]. However, while these technologies offer immense promise, their implementation in the AEC industry is accompanied by a multitude of challenges [21,24-27].

**Material constraints:**

One of the primary hurdles in 4D/5D/6D printing technology is the limited availability of suitable materials. For 4D printing, materials must exhibit dynamic properties, enabling them to alter their shape, size, or functionality over time. Discovering materials that are both durable, cost-effective, and environmentally friendly presents a significant obstacle. Likewise, integrating cost-effective and sustainable materials for 5D and 6D printing poses challenges concerning both procurement and compatibility with existing construction materials.

**Technological limitations:**

AEC professionals necessitate specialized software and hardware to effectively implement 4D/5D/6D printing technology. The industry requires advanced design software capable of creating dynamic, cost-integrated, and sustainable models. Additionally, it demands 3D printers capable of handling advanced materials and producing intricate designs. The high cost associated with acquiring and maintaining these technologies can deter many smaller firms within the industry.

**Complexity of implementation:**

Integrating 4D/5D/6D printing technology entails a steep learning curve. AEC professionals must undergo training to adeptly employ these new tools and techniques. The integration of these technologies into existing workflows and project management systems can disrupt established processes, demanding significant time and effort for adaptation. Resistance to change within the industry can considerably slow down the adoption process.

**Regulatory and standards challenges:**

The AEC industry is heavily regulated, adhering to various building codes and standards to ensure safety and compliance. The introduction of 4D/5D/6D printing technology necessitates updating these regulations to accommodate innovative designs and materials. Establishing new standards for testing and certifying 4D-printed materials and structures is vital to guarantee their reliability and safety.

**Cost implications:**

While 4D/5D/6D printing technology has the potential to enhance efficiency and reduce construction costs over time, the initial investment is substantial. Small and medium-sized companies may find it challenging to justify this expenditure, especially when they have uncertainty about the technology's long-term benefits. Additionally, cost estimation in 5D printing demands accurate data and specialized software, which can be expensive to acquire and maintain.

**Supply chain challenges:**

The implementation of 4D/5D/6D printing technology requires a dependable supply chain for specialized materials and components. Delays or disruptions in the supply chain can significantly impact construction schedules and inflate project costs. Ensuring a consistent supply of high-quality materials is crucial for the successful implementation of these technologies.

**Sustainability and environmental concerns:**



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While 4D/5D/6D printing technologies offer the potential to enhance sustainability in the AEC industry, concerns arise regarding the environmental impact of new materials and manufacturing processes. The industry must address issues related to the recyclability of 4D-printed materials and the environmental footprint of 3D printing processes. Striking a balance between innovation and environmental responsibility is a critical challenge.

**Collaboration and communication:**

Effective collaboration among various stakeholders, including architects, engineers, contractors, and clients, is essential for the success of construction projects. Implementing 4D/5D/6D printing technology requires seamless communication and collaboration throughout the project lifecycle. Ensuring that all involved parties are well- informed and capable of working with the new technologies presents a significant challenge.

**Data security and privacy:**

With the integration of advanced technologies, there is a growing concern about data security and privacy. AEC projects involve sensitive information, and protecting this data from cyber threats is crucial. Implementing robust cybersecurity measures to safeguard design files, project plans, and other confidential data is a challenge that the industry must address.

**Cultural and mindset shift:**

The introduction of 4D/5D/6D printing technology necessitates a cultural shift within the AEC industry. Professionals must adopt a mindset of innovation and continuous learning. Overcoming resistance to change and fostering a culture that encourages experimentation and adaptation is a significant challenge. Companies must invest in training and development programs to upskill their workforce and prepare them for the future of construction technology.

## Future Advancements of 4D/5D/6D Printing Technology in AEC

The realm of Architecture, Engineering, and Construction (AEC) has experienced significant transformations, propelled by technological advancements [70-75]. Among the innovative frontiers within this domain, 4D, 5D, and 6D printing technologies stand out [15,17,19]. These multidimensional printing techniques possess the potential to revolutionize the entire lifecycle of buildings—from design and construction to maintenance.

### Future advancements in 4D printing

**Smart materials and nanotechnology:**

Future advancements in 4D printing will be propelled by the development of intelligent materials and nanotechnology [76-80]. Scientists and engineers are focusing on materials that can respond more efficiently to various stimuli, with nanotechnology enabling the fabrication of intricate structures at the molecular level, enhancing the capabilities of 4D printed objects.

**Enhanced customization:**

Progress in 4D printing will lead to highly personalized and adaptive structures. Architects will design buildings that can change configurations based on environmental conditions or user requirements, such as adaptive facades adjusting permeability based on sunlight and temperature, thereby improving energy efficiency.

**Collaboration with artificial intelligence:**

Integration of 4D printing technology with artificial intelligence (AI) will enable predictive modeling and simulations [7,8,81-87]. AI algorithms can analyze data from various sources, predict potential construction issues, and optimize designs for enhanced efficiency, reducing errors in the construction process [85,87].

### Future advancements in 5D printing

**Real-time cost estimations:**

Future advancements in 5D printing will focus on real-time cost estimations using sophisticated algorithms [88- 95]. These algorithms will consider factors such as material costs, labor expenses, equipment usage, and project timelines, providing accurate and updated cost estimates throughout the construction process.

**Advanced project scheduling:**

5D printing will enable precise project scheduling by integrating with Building Information Modeling (BIM) systems [96-100]. Construction professionals can create detailed schedules, track progress in real-time, and identify potential delays. Advanced analytics and AI algorithms will optimize schedules, ensuring efficient resource utilization and timely project completion.

**Blockchain integration for financial transparency:**

Blockchain technology will be integrated into 5D printing processes to enhance financial transparency and accountability [101-103]. Smart contracts on the blockchain will automate payments, ensuring prompt payment to contractors and suppliers upon fulfilling their obligations. Such integration can reduce disputes, enhance trust, and streamline financial transactions within the industry [104-108].

### Future advancements in 6D printing

**Comprehensive environmental impact analysis:**

Future advancements in 6D printing technology will focus on developing tools for analyzing the environmental impact of construction projects comprehensively [109-115]. These tools will consider factors like carbon footprint, energy consumption, waste generation, and water usage, providing detailed insights for stakeholders to make informed decisions, minimizing ecological harm.

**Sustainable materials and recycling:**

6D printing will promote the adoption of sustainable materials in construction [116-121]. Researchers are developing eco-friendly materials that can be 3D printed and reused in subsequent projects [122-126]. Additionally, such advancements in recycling technologies reducing the industry's environmental footprint [110,127-131].

**Energy-efficient building systems:**

Integration of 6D printing with energy modeling software will



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lead to highly efficient building systems. Future buildings will feature 3D printed components optimizing energy usage, harnessing renewable energy sources, and enhancing overall sustainability [132-139]. Smart HVAC systems, lighting controls, and insulation materials will seamlessly integrate into the construction process, ensuring energy efficiency and reduced operational costs [140- 143].

## Conclusions

This research thoroughly explored the applications, challenges, and future advancements of 4D/5D/6D printing technology in the AEC sector, shedding light on the vast possibilities and complexities associated with these cutting-edge techniques. One of the most significant findings of this research is the wide range of applications that 4D, 5D, and 6D printing technologies offer to architects, engineers, and construction professionals. 4D printing, involving materials that can transform or self-assemble over time, enables the creation of dynamic structures that adapt to changing environmental conditions. In architecture, this translates to intelligent buildings that respond to weather patterns, ensuring energy efficiency and occupant comfort. 5D printing integrates cost estimation into the design and construction process, offering real-time data on project expenses. This integration allows for more accurate budgeting, reducing the likelihood of cost overruns and delays. Consequently, the AEC industry can optimize project timelines and resources, leading to streamlined construction processes and increased overall efficiency. Additionally, 6D printing, incorporating sustainability parameters, facilitates the development of eco-friendly structures. By using environmentally conscious and energy-efficient materials, architects and engineers can make substantial contributions to the global sustainability agenda. These applications underscore the transformative potential of 4D/5D/6D printing technology in revolutionizing the AEC industry.

Nevertheless, these transformative technologies come with challenges that the industry must address to fully leverage their potential. The research identified several obstacles, including the high initial costs of 4D/5D/6D printing equipment, the need for specialized expertise, and the absence of standardized processes and materials. Ethical concerns related to autonomous construction processes and their impact on traditional labor markets also loom large. Addressing these challenges necessitates collaborative efforts from various stakeholders, including industry professionals, researchers, policymakers, and technology developers. Investments in research and development are crucial to advancing 4D/5D/6D printing technology, making it more accessible and cost-effective for widespread adoption. Standardization efforts are equally important, ensuring compatibility between different printing systems and materials, fostering interoperability, and promoting a seamless exchange of information across the industry. Looking ahead, the future of the AEC industry appears promising as 4D/5D/6D printing technology continues to evolve. Researchers and innovators are exploring novel materials, refining printing techniques, and enhancing automation processes, all of which contribute to the technology's maturity. With the intersection of advancements in artificial intelligence and machine learning with 4D/5D/6D printing, we can anticipate even more sophisticated and intelligent structures, capable of adapting to complex and dynamic environments in real-time. Furthermore, collaboration between academia and industry will be pivotal in shaping the future of these technologies. Research institutions can focus on fundamental studies, pushing the boundaries of materials science and engineering principles. Industry partners, on the other hand, can provide valuable insights into practical applications, driving innovation based on real-world challenges and requirements. Embracing these technologies will undoubtedly propel the AEC industry into a new dimension of creativity, efficiency, and sustainability, shaping the skylines of tomorrow in ways we can only begin to imagine.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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