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REVIEW

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3D, 4D, and 5D printing in Architecture, Engineering, and Construction (AEC) industry: applications, challenges, and future scope

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ABSTRACT

The Architecture, Engineering, and Construction (AEC) industry is undergoing a revolutionary transformation, because of integration of cutting-edge printing technologies such as 3D, 4D, and 5D printing. This research delves deep into these advanced techniques, exploring their applications, challenges, and future potential within the AEC sector. The study meticulously examines the diverse applications of 3D printing, ranging from rapid prototyping to intricate architectural models. Additionally, it explores the transformative potential of 4D printing, where materials can change their properties over time, enabling self-assembly and adaptability. The research also delves into the emerging field of 5D printing, emphasizing its role in incorporating cost and time dimensions, thus revolutionizing project management and execution in construction projects. In addressing challenges, this research navigates complexities such as material selection, scalability, and structural integrity. Ethical considerations and environmental impacts associated with these techniques are critically examined. The study also emphasizes the industry's skills gap, highlighting the need for specialized training and expertise to fully harness the potential of 3D, 4D, and 5D printing technologies. Looking ahead, the research paints a compelling vision for the future of AEC. It envisions a landscape where 3D, 4D, and 5D printing technologies become ubiquitous, driven by advancements in materials science, automation, and artificial intelligence. These innovations have the potential to redefine architectural design and construction practices fundamentally. The study underscores the importance of interdisciplinary collaboration, advocating increased partnerships between architects, engineers, material scientists, and technologists. This collaboration is essential for fostering innovation and addressing challenges posed by these emerging technologies. This research provides a comprehensive overview of 3D, 4D, and 5D printing in the AEC industry, offering valuable insights for practitioners, researchers, and policymakers. By unraveling the applications, challenges, and future prospects of these technologies, the study illuminates a transformative path for the AEC sector. It envisions a future where the boundaries of creativity and efficiency are redefined through the fusion of digital ingenuity and physical construction.

KEYWORDS

3D Printing; 4D printing; 5D printing; Additives; 3D printers; Engineering; Construction

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Introduction

In recent years, the Architecture, Engineering, and Construction (AEC) industry has witnessed a transformative wave with the rapid progression of additive manufacturing technologies [1-4]. These innovations have not only supplemented but in some instances supplanted traditional manufacturing methods [3,4]. Novel techniques like 3D, 4D, and 5D printing have emerged as game-changers, redefining the way structures are conceptualized and constructed, ushering in unprecedented possibilities and challenges at the nexus of technology and construction. 3D printing, also referred to as additive manufacturing, entails the layer-by-layer creation of three-dimensional objects from digital blueprints [2,4]. Its applications in architecture have been profound, allowing architects to swiftly and precisely manifest intricate designs into tangible prototypes. In the realm of engineering, 3D printing has disrupted conventional prototyping, enabling engineers to craft complex components, refine designs, and enhance product performance. Furthermore, in the construction domain, 3D printing has set the stage for the construction of entire edifices, promising heightened efficiency and cost reduction [5-7].

4D printing, an extension of 3D printing, introduces the dimension of time. This groundbreaking technology utilizes materials that can metamorphose or self-assemble over time when exposed to external stimuli like heat, water, or light [8-10]. In the AEC sector, 4D printing opens doors to adaptive and responsive structures capable of adapting to environmental shifts, thus optimizing functionality and sustainability [9,10]. The latest evolution, 5D printing, melds data-driven decision-making with the physical construction process. By integrating real-time data and feedback loops, 5D printing enables dynamic adjustments during construction, augmenting efficiency, minimizing errors, and maximizing resource utilization [11-13]. This innovation holds the potential to revolutionize project management and cost estimation in the AEC industry. Nonetheless, alongside the

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plethora of opportunities presented by these advanced printing technologies, significant challenges must be surmounted. Concerns encompass material limitations, structural integrity, scalability, and standardization. Furthermore, ethical, legal, and regulatory issues related to intellectual property, safety, and environmental impact necessitate meticulous attention [14-16]. The objective of this research is to comprehensively delve into the applications, challenges, and future potential of 3D, 4D, and 5D printing in the AEC industry. By scrutinizing their innovative applications within architecture, engineering, and construction and critically evaluating the hurdles encountered during implementation, this study aims to offer valuable insights into the evolving landscape of construction technologies. Additionally, by forecasting the future trajectory of these technologies, it seeks to inform the strategies and policies of the AEC industry, ensuring a sustainable, efficient, and technologically advanced future. Figure 1 shows the co-occurrence analysis of the keywords in literature.

3D Printing in AEC Industry

In recent years, 3D printing technology has emerged as a revolutionary innovation with transformative potential across diverse industries [3,5,7]. One sector profoundly impacted by this technology is the Architecture, Engineering, and Construction (AEC) industry [17-25].

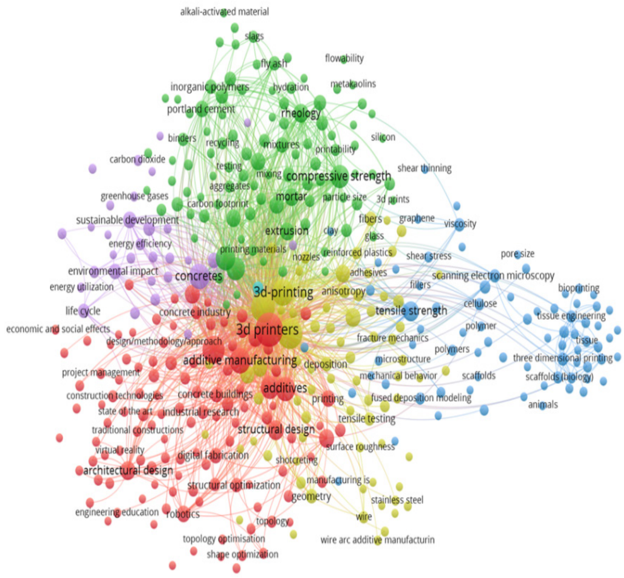

Figure 1. Co-occurrence analysis of the keywords in literature.

Table 1 shows the applications, challenges and future scope of 3D printing in the AEC industry.

Table 1. Applications, challenges and future scope of 3D printing in AEC industry.

S/N.	Aspect	Applications	Challenges	Future Scope
1	Architecture	- Customized Interiors: Designing bespoke furniture, lighting fixtures, and interior décor elements tailored to specific designs and client preferences. - Historical Preservation: Replicating and restoring historical architectural elements and sculptures with high precision. - Temporary Structures: Constructing pavilions, exhibition booths, and event structures with intricate designs. - Architectural Art: Crafting artistic sculptures and installations blending aesthetics with functionality. - Prototyping: Creating architectural prototypes and scale models for visualization and client presentations.	- Limited material variety and scalability for large projects. - Integrating 3D printing with traditional construction methods. - Complex design detailing and integration challenges. - Cost-effectiveness and speed for mass customization.	- Development of recyclable and biodegradable materials. - Advancements in AR and VR for immersive architectural experiences. - Collaborative platforms for architects and 3D printing experts. - 3D printing of dynamic and responsive architectural structures.
2	Engineering	- Prototyping: Creating prototypes for testing and validation of engineering products. - Education and Research: Producing tangible models for academic and experimental use. - Jigs and Fixtures: Designing specialized tools and components for manufacturing processes. - Complex Components: Building intricate components for aerospace and automotive industries.	- Material durability and precision requirements. - Compliance with industry standards and certifications. - Post-processing for desired surface finish. - Integration with AI for predictive modeling and optimization.	- Advancements in high-temperature and high-strength materials. - Expansion into biomedical field for functional organ printing. - Industry-specific standards for 3D printed engineering components. - AI-driven optimization for complex engineering designs.

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3	Constructio n	- Emergency Response: Rapidly deploying shelters and housing solutions in disaster-stricken areas. - Infrastructure Components: Printing bridge parts, drainage systems, and road barriers. - Prefabrication: Manufacturing modular building components for on-site assembly. - Sustainable Construction: Creating eco-friendly structures with minimal material wastage. - Renovation: Repairing and retrofitting existing structures.	- Regulatory compliance and building code adherence. - Energy efficiency of 3D printing processes. - Limited awareness and acceptance among construction professionals. - Transportation and logistics for large-scale printed components.	- Development of 3D printed smart structures with embedded sensors. - Exploration of self-healing materials for infrastructure longevity. - Customization of construction projects based on local environmental conditions. - Collaboration between architects, engineers, and construction firms for seamless 3D printing integration.

Architecture

Conceptualization and design:

3D printing has profoundly impacted architectural conceptualization and design. Architects can effortlessly craft intricate scale models of their designs, enabling clients and stakeholders to comprehensively visualize the final structure. This technology empowers architects to experiment with complex geometries and organic forms, which would be challenging or impossible with traditional methods. By swiftly translating digital blueprints into physical models, architects can iteratively refine their designs, fostering innovative and efficient architectural solutions.

Prototyping and iterative design

3D printing expedites prototyping, enabling architects to test their ideas swiftly and make necessary adjustments. Unlike time-consuming traditional methods, 3D printing allows architects to create multiple design iterations rapidly, fostering exploration of different concepts and efficient vision refinement. This iterative design approach results in higher-quality architectural solutions that are both functional and aesthetically pleasing.

Customization and personalization

3D printing facilitates architectural customization according to individual client needs. From decorative facades to interior fixtures, architects can create unique, personalized designs catering to specific requirements. This level of customization enhances user experience and satisfaction, tailoring buildings to occupants' needs.

Sustainable architecture

Sustainability is a paramount concern in modern architecture. 3D printing enables architects to utilize eco-friendly materials and optimize designs for minimal waste. Architects can experiment with innovative materials, like biodegradable or recycled plastics, to create environmentally friendly structures. By reducing material wastage and energy consumption, 3D printing fosters sustainable architectural practices. Figure 2 shows the co-authorship analysis.

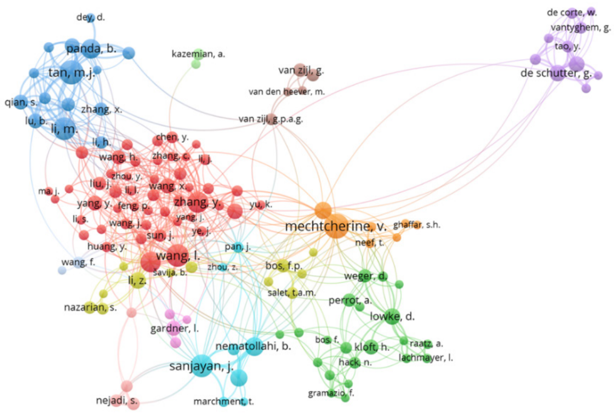

Figure 2. Co-authorship analysis.

Engineering

Prototyping and testing

Engineers utilize 3D printing extensively for prototyping and testing components and systems. Creating physical prototypes is crucial for evaluating functionality and performance. 3D printing allows engineers to produce prototypes rapidly and cost-effectively, facilitating identification of design flaws and product optimization before mass production.

Structural analysis and simulation

3D printing facilitates the creation of intricate structural models representing real-world conditions. Engineers employ these models for in-depth structural analysis and simulation, ensuring buildings and infrastructure projects are engineered to withstand diverse environmental factors and loads, ensuring safety and longevity.

Complex components and parts

In industries like aerospace and automotive engineering, 3D printing excels in producing intricate components challenging to manufacture traditionally. Engineers create lightweight, high-strength components with intricate internal structures, enhancing various systems' performance.

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Customized tools and equipment

Engineers require specialized tools tailored to specific tasks. 3D printing enables the rapid design and production of customized tools, enhancing efficiency and productivity in various engineering processes.

Construction

Prefabricated construction

3D printing transforms construction by enabling prefabricated building components' production. Entire walls, facades, and structural elements can be 3D printed off-site, reducing construction timelines, labor costs, and material wastage. Prefabrication ensures higher precision and consistency, improving overall quality.

On-site construction

Large-scale 3D printers can create entire buildings layer by layer on-site, eliminating traditional formwork and reducing dependence on skilled labor. This flexibility allows construction of unconventional, innovative structures challenging traditional methods.

Affordable housing solutions

3D printing addresses the global housing crisis by providing affordable and rapidly deployable housing solutions. Using locally sourced materials, 3D printers construct low-cost houses quickly, transforming slums and disaster-stricken areas, providing safe and sustainable housing.

Infrastructure development

Beyond building construction, 3D printing finds applications in infrastructure development. Bridges, tunnels, and critical components can be 3D printed with high precision, ensuring functionality and architectural appeal. On-site spare parts printing reduces downtime, enhancing infrastructure systems' overall efficiency.

4D Printing in AEC Industry

In technological advancements, 3D printing has long been a pioneer, revolutionizing various industries with its capacity to transform digital designs into three-dimensional objects [2,4]. However, a new dimension has quite literally emerged in the form of 4D printing, which has the potential to reshape the landscape of architecture, engineering, and construction (AEC) in unprecedented ways [9,10]. The term "4D printing" refers to 3D printed objects capable of self-transformation over time in response to external stimuli such as heat, water, light, or environmental factors. This transformative capability extends the possibilities of traditional 3D printing, opening doors to innovative solutions in the AEC industry [8,9].

Advancements in architectural design

Adaptive architecture

4D printing empowers architects to create dynamic structures that respond to environmental changes, adjusting their shapes or configurations based on sunlight, temperature, or occupancy. This optimization enhances energy efficiency and occupant comfort, ultimately reducing energy consumption and promoting sustainability.

Customization and complex geometries

Traditional construction methods often impose limits on architects' ability to realize intricate designs. 4D printing allows for the creation of complex geometries and customized architectural elements that were previously challenging or impossible to construct. This customization not only enhances aesthetics but also improves functionality, enabling architects to design structures tailored to specific needs and contexts.

Temporary structures and events

4D printing proves valuable in the creation of temporary structures, such as event pavilions or emergency shelters. These structures can be designed to self-assemble or transform upon deployment, simplifying construction processes and ensuring rapid response during emergencies or events, where quick, efficient, and temporary solutions are required.

Innovations in engineering

Smart infrastructure

4D printing introduces the concept of "smart infrastructure," where civil engineering projects like bridges and roads can adapt to changing conditions. Bridges, for example, can change their shapes based on varying loads or environmental stresses, ensuring optimal structural integrity and enhancing safety and longevity, addressing challenges associated with ageing infrastructure.

Self-healing materials

The integration of 4D printing with self-healing materials offers a groundbreaking solution to material degradation and structural damage. Structures constructed with self-healing materials can autonomously detect and repair cracks or damages, significantly reducing maintenance costs and extending the lifespan of buildings and infrastructure.

Optimized construction processes

4D printing streamlines construction processes by enabling the use of pre-programmed, self-assembling components. This automation reduces labour-intensive tasks and construction time, leading to cost savings and increased efficiency. The ability to print complex, prefabricated components on-site minimizes waste and enhances construction accuracy.

Transformative impacts on construction

Modular construction

4D printing stands to benefit the modular construction industry significantly. Modular buildings consist of prefabricated modules that can be assembled on-site. 4D printing allows for the creation of modules that can self-assemble or transform upon installation, providing flexibility in building configurations and accommodating diverse functions. This approach significantly accelerates construction timelines, making it an attractive option for various projects, from housing developments to commercial spaces.

Disaster relief and humanitarian aid

In disaster-stricken areas, rapid construction of shelters and infrastructure is critical. 4D printing enables the creation of self-assembling structures, providing quick and efficient relief

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in emergency situations. These structures can be designed to withstand harsh conditions and adapt to the specific needs of affected communities, ensuring safe and resilient shelter solutions.

Sustainable construction

Sustainability is a paramount concern in the AEC industry. 4D printing, coupled with eco-friendly materials, can revolutionize sustainable construction practices. The ability to create self-assembling, energy-efficient structures reduces the environmental impact associated with traditional construction methods. Additionally, the use of recycled or biodegradable materials in 4D printing further promotes sustainable building practices, aligning with global efforts to mitigate climate change.

4D printing represents a groundbreaking evolution in the AEC industry, offering a paradigm shift in how we conceptualize, design, and construct buildings and infrastructure [9,10]. From adaptive architectures and smart infrastructure to modular construction and sustainable building practices, the applications of 4D printing are vast and transformative. As the technology matures and barriers are overcome, it has the potential to revolutionize the way we approach construction, ushering in an era of dynamic, efficient, and sustainable built environments. The integration of 4D printing not only enhances the aesthetics and functionality of structures but also addresses critical challenges such as rapid construction in disaster-stricken areas, infrastructure resilience, and environmental sustainability [8,10]. As researchers, engineers, and architects continue to push the boundaries of what 4D printing can achieve, the industry is poised for a future where buildings and infrastructure are not static entities but living, adaptable organisms, responding to the needs of the environment and the people they serve. The journey towards realizing this future is underway, promising a transformative impact on the way we perceive and interact with the built world. Table 2 shows the applications, challenges and future scope of 4D printing in AEC industry.

Table 2. Applications, challenges and future scope of 4D printing in AEC industry.

S/N.	Category	Applications	Challenges	Future Scope
1	Architecture	1. Adaptive Structures: Self-assembling buildings and furniture. 2. Shape-Morphing Facades: Facades responding to environmental conditions. 3. Dynamic Interiors: Interior spaces adapting to user needs.	1. Material Limitations: Limited suitable materials. 2. Design Complexity: Intricate designs needing advanced software and precision.	1. Advanced Materials: Development of enhanced 4D printing materials. 2. Innovative Design: Integration into cutting-edge architectural concepts.
2	Engineering	1. Smart Infrastructure: Self-repairing roads and bridges. 2. Tunable Structures: Components with adjustable properties. 3. Responsive Mechanisms: Mechanical parts reacting to changing conditions.	1. Structural Integrity: Ensuring printed structures meet safety standards. 2. Cost Challenges: Initial setup and material expenses.	1. Structural Optimization: Algorithms for maximizing 4D printed structure efficiency. 2. Standardization: Establishing industry-wide 4D printing practices.
3	Construction	1. On-site Assembly: Self-assembling construction components. 2. Adaptable Building Layouts: Buildings changing configurations based on need. 3. Efficient Insulation Systems: Adaptive insulation adjusting to environmental conditions.	1. Scaling Printing: Upscaling for large construction projects. 2. Workforce Training: Training labor for 4D printing technology.	1. Robotic Integration: Merging 4D printing with robotics for automated construction. 2. Sustainable Practices: Eco-friendly materials and methods for 4D printing.

5D Printing in AEC Industry

The Architecture, Engineering, and Construction (AEC) sector has consistently been a pioneer in embracing technological advancements [7,10,13]. Among the latest groundbreaking innovations in this field, 5D printing stands out. Traditional 3D printing has already transformed the process of creating prototypes and manufacturing products [3,6]. However, 5D printing takes this technology to the next level by adding two

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crucial dimensions: time and cost. While traditional 3D printing builds three-dimensional objects layer by layer, 5D printing introduces the element of time, simulating an object's behaviour and changes over time [11-13]. Moreover, it considers the financial implications related to various factors like materials, labour, and time. In essence, 5D printing offers a holistic view of a project's lifecycle. This capability empowers architects, engineers, and construction professionals to make informed decisions from the initial design phase to project completion [11,12]. This technology merges Building Information Modeling (BIM) with 3D printing, resulting in a potent tool that enhances collaboration, visualization, and project management.

Applications of 5D printing in architecture

Conceptualization and prototyping

5D printing revolutionizes the initial phases of architectural projects. Architects can now craft intricate and precise models that faithfully represent their creative concepts. This technology enables rapid prototyping, allowing architects to visualize their designs in tangible forms. This streamlines the design process and enhances communication with clients, making it easier to convey complex design ideas.

Customization and complex geometries

5D printing empowers architects to explore unprecedented levels of customization. Complex architectural elements that were once challenging to create using traditional methods can now be realized with 5D printing. This technology enables architects to experiment with innovative designs, pushing the boundaries of conventional architecture. From facades to interior decor, 5D printing opens up endless possibilities for creating distinctive, aesthetically pleasing structures.

Applications of 5D printing in engineering

Structural analysis and simulation

Engineers can utilize 5D printing to create detailed structural models for analysis and simulation. By incorporating the element of time, engineers can assess how different materials and structural configurations behave under various conditions, such as stress, load, and environmental factors. This real-time simulation enhances the accuracy of structural analysis, leading to more robust and resilient designs.

Prototyping and testing

In engineering, prototyping and testing are essential phases for validating designs before mass production. 5D printing allows engineers to rapidly prototype components and conduct comprehensive tests. This iterative process enables engineers to identify potential issues early in the design stage, reducing costly errors and ensuring the final product meets the desired specifications.

Applications of 5D printing in construction

Prefabrication and on-site assembly

5D printing streamlines the prefabrication of construction components with intricate designs. These prefabricated elements can be produced off-site with precision and then assembled on-site, reducing construction time and labor costs. Moreover, the ability to 5D print complex structural components enhances the efficiency of on-site assembly, contributing to faster project completion.

Cost estimation and budgeting

Accurate cost estimation is a critical aspect of construction projects. 5D printing integrates cost data into digital models, allowing for precise cost estimation and budgeting. Construction professionals can analyze different scenarios, materials, and labour costs in real-time. This dynamic approach to budgeting enables more precise financial planning, helping stakeholders make informed decisions and avoid budget overruns.

5D printing is unquestionably reshaping the landscape of the Architecture, Engineering, and Construction industry. Its multi-dimensional approach, which incorporates time and cost factors, has far-reaching implications for architectural design, engineering processes, and construction methods. The ability to create intricate, customized designs, simulate real-time structural behaviour, and optimize cost estimation makes 5D printing a game-changing technology. As the industry continues to explore the full potential of 5D printing, stakeholders need to collaborate, invest in research and development, and address challenges related to cost, standardization, and sustainability. With ongoing advancements and strategic implementation, 5D printing has the potential to revolutionize how we conceptualize, design, and construct buildings, ushering in a new era of innovation, efficiency, and sustainability in the AEC industry.

Challenges and Future Scope of 3D, 4D, and 5D Printing in AEC Industry

3D, 4D, and 5D printing stand as groundbreaking technologies with immense promise within the Architecture, Engineering, and Construction (AEC) sector [6,9,11]. Within this realm, each technology presents distinct challenges and future opportunities.

3D printing

Challenges

Material limitations: Presently, 3D printing materials lack the necessary strength for structural components, demanding the discovery of suitable construction-grade materials.

Scale and speed: Large-scale 3D printing is sluggish and costly, necessitating advancements in speed and scalability for practical application.

Design complexity: Embracing 3D printing demands a paradigm shift in design thinking; architects and engineers must adopt new approaches to maximize the technology's benefits.
Regulatory hurdles: Existing construction codes are not tailored for 3D printing, demanding adaptations in regulations to accommodate this transformative technology.
Future scope

Sustainable construction: 3D printing minimizes waste and optimizes material usage, promoting environmentally friendly construction practices.

Customization: This technology enables intricate and

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personalized designs, empowering architects to craft distinctive and aesthetically pleasing structures.

Remote construction: 3D printing's potential in constructing buildings in remote or challenging environments can revolutionize disaster relief and off-grid construction.

4D printing

Challenges

Material properties: Developing materials that can change shape or strength over time poses a significant challenge.

Control and automation: Ensuring precise control and automation in the transformation process for 4D-printed structures is intricate.

Design complexity: Creating structures that can dynamically change requires a profound understanding of underlying principles and mechanics.
Future scope

Adaptive architecture: 4D printing can lead to adaptive buildings that respond to environmental changes, enhancing energy efficiency and occupant comfort.

Self-healing structures: Materials capable of self-repair through 4D printing could extend construction project lifespans.

Reduced maintenance: Buildings that adapt and repair themselves could significantly reduce the need for frequent maintenance and repairs.

5D printing

Challenges

Complexity: Integrating 3D printing with time (4D) and additional data dimensions (e.g., cost, material availability) introduces complexity in design, execution, and management.
Data integration: Gathering and integrating real-time data for cost, schedule, and materials can be challenging.

Interoperability: Ensuring seamless communication and collaboration among various software and hardware systems used in 5D printing is a technical challenge.
Future scope

Cost and resource optimization: 5D printing optimizes construction projects by continuously assessing and adapting to changing parameters like cost and resource availability.
Real-time decision-making: Integrated data enables real-time decision-making, enhancing project efficiency and reducing errors.

Smart cities: 5D printing contributes to smart city development by enabling real-time monitoring and control of infrastructure.
3D, 4D, and 5D printing have transformative potential within the AEC industry, albeit with unique challenges. As technology advances and professionals and regulators adapt, these printing technologies have the potential to revolutionize how we design, construct, and manage buildings and infrastructure, offering increased sustainability, adaptability, and efficiency in the industry.

Conclusion

In the changing landscape of the Architecture, Engineering, and Construction (AEC) industry, the integration of cutting-edge technologies has become essential for sustainable growth and progress. Within this realm, 3D, 4D, and 5D printing have emerged as transformative tools, reshaping how we conceive, design, and construct our built environment. The applications of 3D printing in AEC are diverse, ranging from rapid prototyping and crafting intricate architectural models to constructing entire buildings with complex designs once deemed unachievable. 4D printing introduces the element of time, allowing structures to adapt based on environmental cues, and enhancing resilience and sustainability. Simultaneously, 5D printing, incorporating cost considerations, offers a holistic approach to project management and budgeting. Together, these technologies have paved the way for revolutionary progress in architecture, engineering, and construction, encouraging creativity and pushing the boundaries of what's possible. Yet, the widespread adoption of 3D, 4D, and 5D printing in the AEC industry faces challenges. Technological limitations, material constraints, and regulatory hurdles present significant barriers. Workforce upskilling is necessary to fully utilize these technologies. Ethical and environmental concerns, such as sustainable material sourcing and waste reduction, demand careful attention. Addressing these challenges requires collaborative efforts from researchers, industry professionals, policymakers, and educators to drive innovation and establish best practices.

Looking ahead, the future of 3D, 4D, and 5D printing in the AEC industry appears promising, necessitating strategic planning and continuous research. Advances in materials science, particularly in eco-friendly and high-performance construction materials, will broaden the applications of these technologies. Additionally, integrating artificial intelligence (AI) and machine learning (ML) algorithms will enhance printing precision and efficiency, leading to faster construction and reduced costs. Moreover, overcoming the challenges associated with 3D, 4D, and 5D printing demands a collaborative approach. Industry stakeholders must partner with research institutions to invest in overcoming material limitations, improving printing speed, and ensuring structural integrity. Regulatory bodies need to collaborate with innovators to establish standards ensuring the safety and reliability of 3D-printed structures. Tailored education and training programs are essential to equip the workforce with the skills to leverage these technologies effectively.

3D, 4D, and 5D printing are ushering in a new era for the AEC industry, where creativity merges with functionality, and sustainability meets innovation. While challenges persist, they are surmountable. Through collective efforts, the AEC industry can harness the full potential of these printing technologies, creating a built environment that is not only aesthetically captivating but also structurally robust, environmentally conscious, and economically feasible. Collaboration, innovation, and a shared vision for a sustainable future will be the guiding principles shaping the evolution of 3D, 4D, and 5D printing in the realm of architecture, engineering, and construction.

Disclosure statement

No potential conflict of interest was reported by the author.

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References

1. Tay YW, Panda B, Paul SC, Noor Mohamed NA, Tan MJ, Leong KF. 3D printing trends in building and construction industry: a review. Virtual Phys Prototyp. 2017;12(3):261-276. https://doi.org/10.1080/17452759.2017.1326724
2. El-Sayegh S, Romdhane L, Manjikian S. A critical review of 3D printing in construction: Benefits, challenges, and risks. Arch Civ Mech Eng. 2020;20:1-25. https://doi.org/10.1007/s43452-020-00038-w
3. Hossain MA, Zhumabekova A, Paul SC, Kim JR. A review of 3D printing in construction and its impact on the labor market. Sustainability. 2020;12(20):8492. https://doi.org/10.3390/su12208492
4. Holt C, Edwards L, Keyte L, Moghaddam F, Townsend B. Construction 3D printing. In 3D Concrete Printing Technology. 2019:349-370. https://doi.org/10.1016/B978-0-12-815481-6.00017-8
5. Vatin NI, Chumadova LI, Goncharov IS, Zykova VV, Karpenya AN, Kim AA, et al. 3D printing in construction. Stroitel'stvo Unikal'nyh Zdanij i Sooruzenij. 2017(1):27. https://doi.org/10.18720/CUBS.52.3
6. Besklubova S, Skibniewski MJ, Zhang X. Factors affecting 3D printing technology adaptation in construction. J Constr Eng Manag. 2021;147(5):04021026. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002034
7. Hager I, Golonka A, Putanowicz R. 3D printing of buildings and building components as the future of sustainable construction? Procedia Eng. 2016;151:292-299. https://doi.org/10.1016/j.proeng.2016.07.357
8. Pacillo GA, Ranocchiai G, Loccarini F, Fagone M. Additive manufacturing in construction: A review on technologies, processes, materials, and their applications of 3D and 4D printing. Mater Des Process Commun. 2021;3(5):e253. https://doi.org/10.1002/mdp2.253
9. Zhang Z, Demir KG, Gu GX. Developments in 4D-printing: a review on current smart materials, technologies, and applications. Int J Smart Nano Mater. 2019;10(3):205-224. https://doi.org/10.1080/19475411.2019.1591541
10. Ramesh S, Kiran reddy S, Usha C, Naulakha NK, Adithyakumar CR, Lohith Kumar Reddy M. Advancements in the research of 4D printing-a review. In IOP Conf Ser Mater Sci Eng. 2018;76:012123. https://doi.org/10.1088/1757-899X/376/1/012123
11. Anas S, Khan MY, Rafey M, Faheem K. Concept of 5D printing technology and its applicability in the healthcare industry. Mater Today Proc. 2022;56:1726-1732. https://doi.org/10.1016/j.matpr.2021.10.391
12. Aruna R, Mohamed Abbas S, Vivek S, Suresh G, Meenakshi CM, Srinivasan T, et al. Evolution of 5D Printing and Its Vast Applications: A Review. Recent Advances in Materials and Modern Manufacturing: Select Proceedings of ICAMMM 2021. 2022:691-714. https://doi.org/10.1007/978-981-19-0244-4_66
13. Reddy PR, Devi PA. Review on the advancements of additive manufacturing-4D and 5D printing. Int J Mech Prod Eng Res Dev. 2018;8(4):397-402.
14. Neely EL. The risks of revolution: Ethical dilemmas in 3D printing from a US perspective. Sci Eng Ethics. 2016;22:1285-1297. https://doi.org/10.1007/s11948-015-9707-4
15. Khunti R. The problem with printing Palmyra: exploring the ethics of using 3D printing technology to reconstruct heritage. Stud Digit Herit. 2018;2(1):1-2. https://doi.org/10.14434/sdh.v2i1.24590
16. Romdhane L, El-Sayegh SM. 3D printing in construction: Benefits and challenges. Int J Struct Civ Eng Res. 2020;9(4):314-317. https://doi.org/10.18178/ijscer.9.4.314-317
17. Al Jassmi H, Al Najjar F, Mourad AH. Large-Scale 3D printing: The way forward. In IOP Conf Ser Mater Sci Eng. 2018;324:012088. https://doi.org/10.1088/1757-899X/324/1/012088
18. Núñez C, Regalado M, Gago A. 3D Printing: An opportunity for the sustainable development of building construction. Proceedings of the International Symposium on Automation and Robotics in Construction. 2023;40:691-698.
19. Prasad KV, Vasugi V, Kumaran GS. Application of 3D printing concepts in the Architecture Engineering and Construction (AEC) industry-a scientometric review. Mater Today Proc. 2023. https://doi.org/10.1016/j.matpr.2023.02.158
20. Saleh Abd Elfatah A. 3D printing in architecture, engineering and construction (concrete 3D printing). J Eng Res. 2019;162:119-137. https://dx.doi.org/10.21608/erj.2019.139808
21. Robayo-Salazar R, de Gutiérrez RM, Villaquirán-Caicedo MA, Arjona SD. 3D printing with cementitious materials: Challenges and opportunities for the construction sector. Autom Constr. 2023;146:104693. https://doi.org/10.1016/j.autcon.2022.104693
22. Pessoa S, Guimarães AS. The 3D printing challenge in buildings. In E3S Web Conf. 2020;172:19005. https://doi.org/10.1051/e3sconf/202017219005
23. Pan Y, Zhang Y, Zhang D, Song Y. 3D printing in construction: state of the art and applications. Int J Adv Manuf Tech. 2021;115(5): 1329-1348. https://doi.org/10.1007/s00170-021-07213-0
24. Ozturk GB. The future of 3D printing technology in the construction industry: a systematic literature review. Eurasian j civ eng archit. 2018;2(2):10-24.
25. Buchanan C, Gardner L. Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges. Eng Struct. 2019;180:332-348. https://doi.org/10.1016/j.engstruct.2018.11.045

https://doi.org/10.61577/scpnmia.2024.100008