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A systematic review of the role of 4D printing in sustainable civil engineering solutions

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ABSTRACT

This systematic review, not financially supported by any funding body, aims to synthesize the current knowledge on the applications, potential benefits, and challenges of 4D printing in civil engineering, with a focus on its role in sustainable solutions. Comprehensive searches were conducted in Scopus, Web of Science, and Google Scholar using related keywords. Articles that discussed 4D printing within civil engineering and construction contexts, encompassing both conceptual and empirical studies, were included. The findings suggest that 4D printing, with its time-responsive transformation feature, can enhance design freedom, improve structural performance, and increase environmental efficiency in construction. However, challenges persist in material performance, scalability, and cost. Despite these, ongoing advancements signal potential future developments that could widen the opportunities for large-scale applications of 4D printing in civil engineering. The potential use of renewable, bio-based materials could also lead to more sustainable construction practices. This review highlights the transformative potential of 4D printing, underlining the need for further research to fully leverage its capabilities and address current limitations. 4D printing emerges as a promising avenue for sustainable civil engineering solutions, offering a transformative approach that calls for continued exploration and development.

1. Introduction

Skylar Tibbits, a professor at the Massachusetts Institute of Technology (MIT), first introduced the concept of 4D printing in a TED talk. He described 4D printing (4DP) as the capacity to program materials to undergo changes in shape, properties, and even process information over time. Since the introduction of this concept, researchers and engineers worldwide have been working to advance and perfect this technology, investigating its potential applications in fields such as architecture, aerospace, and medicine. Civil engineering, a field characterized by continuous innovation, shapes the built environment and infrastructure that underpins our societies. As new technologies emerge, civil engineering adapts, seeking more efficient methods to design, construct, and maintain the structures that surround us [1]. One such technological advancement with the potential to transform civil engineering is 4DP. In this introduction, we will delve into the concept of 4DP and its potential impact on civil engineering.

4DP expands upon the foundation of 3D printing (3DP), a technology that enables the creation of intricate, three-dimensional objects through the layer-by-layer deposition of material. While 3DP has already found numerous applications in civil engineering, from architectural models to full-scale structural components, 4DP propels this technology to new heights. The defining characteristic

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of 4DP is the use of materials that can change their properties and behavior over time in response to external stimuli. These "smart materials," such as shape-memory polymers, hydrogels, and stimuli-responsive composites, enable the creation of structures that can adapt to changing conditions, such as temperature, moisture, and load [2,3].

In the context of civil engineering, 4DP offers several advantages. First, it allows for the development of adaptive and responsive infrastructure, which can improve safety and resilience in the face of natural disasters or extreme weather conditions. For example, a 4D-printed bridge might be able to redistribute load in real-time, ensuring structural integrity even under unexpected stresses. Second, 4DP has the potential to contribute to more sustainable construction practices. By using materials that can be programmed to change their properties, it becomes possible to minimize waste, reduce energy consumption, and create eco-friendly structures. Moreover, 4D-printed components can be designed to self-assemble or self-heal, reducing the need for manual labor and maintenance. Finally, 4DP opens new design possibilities in civil engineering. Complex geometric structures that were previously difficult or impossible to create using traditional methods can now be easily fabricated. This enables architects and engineers to push the boundaries of what is possible, creating structures that are not only functional but also aesthetically striking [4–6].

Scalability is a significant concern when it comes to integrating 4DP into civil engineering. While small-scale prototypes and components have been successfully produced, scaling up this technology for large infrastructure projects presents unique challenges. This requires advancements in the printing process, materials, and equipment to ensure that 4D-printed structures can maintain their adaptive capabilities and structural integrity at larger scales. Material limitations also pose a challenge for 4DP in civil engineering. While smart materials exhibit remarkable properties, they must be balanced against factors such as durability, cost-effectiveness, and compatibility with existing construction materials. Ongoing research and development efforts are needed to identify and refine materials that meet the demands of civil engineering applications without sacrificing the benefits offered by 4DP [2,3].

Maraveas, C. et al. [7] delved into the potential of 4DP technology in producing sustainable plastics for agricultural use. The authors illuminated the advancements in material science, design, and manufacturing processes that have fostered the development of 4DP. This printing technology incorporates the use of smart materials that have the capacity to morph their shape and properties over time, in response to external stimuli. They underscored the potential benefits of employing 4D-printed sustainable plastics in agriculture. These advantages include the deployment of controlled-release systems for fertilizers and pesticides, adaptive irrigation systems, and crop protection structures. Concurrently, they addressed the challenges associated with material development, scalability, and regulatory issues. The authors concluded that 4DP harbors considerable potential for revolutionizing sustainable plastics production within agriculture. They emphasized the necessity for ongoing research, development, and interdisciplinary collaboration to fully realize its potential.

Ameta, K. L. et al. [8] delivered an exhaustive review of the present state and future prospects of 3D and 4DP technologies within the scope of sustainable and environmentally friendly smart manufacturing. The authors explored the advancements in the materials, processes, and applications linked with these printing technologies, along with the challenges and opportunities they pose for sustainable manufacturing. The environmental ramifications of adopting 3D and 4DP were also discussed, such as waste reduction, resource efficiency enhancement, and the promotion of circular economy principles. The review emphasized the potential of these technologies across various industries, including healthcare, aerospace, automotive, and construction. Moreover, it underlined the need for further research, development, and collaboration among stakeholders to tackle the associated challenges and fully exploit the benefits of 3D and 4DP in sustainable and environmentally friendly smart manufacturing.

Ram Kishore, S. et al. [9] conducted a study on the potential of utilizing natural fiber biocomposites in 4DP for sustainable agricultural applications like bio-mulching. The authors thoroughly examined the current state of 4DP technologies and materials, highlighting the benefits of employing natural fibers. These benefits included a reduced environmental impact, enhanced mechanical properties, and increased biodegradability. The potential advantages of using 4D-printed natural fiber biocomposites in agriculture were discussed. These advantages comprised improved soil health, minimized plastic waste, and boosted crop productivity. The article also underscored the challenges and existing research gaps in the field, such as material processing, printability, and long-term performance. This emphasized the necessity for continued research and development to fully tap into the potential of 4D-printed natural fiber biocomposites for sustainable agricultural applications and beyond.

Regulatory challenges must also be considered as 4DP becomes more prevalent in civil engineering. Building codes and standards will need to be updated to accommodate the unique properties and behaviors of 4D-printed structures. This process will require collaboration between researchers, engineers, policymakers, and regulators to ensure that the benefits of 4DP can be realized while maintaining the safety and reliability of the built environment [10].

Alves, J. L. et al. [11] engaged in a comprehensive discussion surrounding the potential applications and challenges of 4DP in the construction industry. The authors scrutinized the current state of 4DP technology, materials, and design methodologies, assessing their potential for fostering adaptive, sustainable, and efficient construction solutions. They further delved into the potential implications of 4DP on construction processes, labor, and environmental factors. The chapter probes into the challenges and constraints related to 4DP in construction, such as material development, printability, and regulatory concerns. In conclusion, the authors suggested prospective research directions and strategies to surmount these challenges, thereby enabling successful implementation of 4DP in the construction sector. They ultimately queried whether 4DP represents a current reality, a glimpse into the future, or is merely a facet of science fiction in the context of construction.

Debrah, C. et al. [12] explored the role of artificial intelligence (AI) in promoting green building practices in their article. The authors studied various AI techniques and algorithms applied in the design, construction, and operation phases of green building projects, highlighting their potential to enhance energy efficiency, reduce environmental impacts, and optimize resource utilization. The study provided a comprehensive review of current AI applications in green buildings, such as building information modeling (BIM), generative design, and performance simulation, as well as their effectiveness in achieving sustainable goals. Additionally, the authors discuss the challenges and limitations associated with the adoption of AI in the green building sector, such as data quality and privacy concerns. The article concluded by proposing future research directions and strategies for harnessing the potential of AI in advancing green building practices, emphasizing the need for interdisciplinary collaboration, improved data management, and continued innovation.

The integration of 4DP into civil engineering mandates a notable shift within the workforce. Professionals such as construction workers, engineers, and architects will need to undertake retraining and upskilling to comprehend and work effectively with 4DP technologies and materials. This calls for a unified effort from educational institutions, professional organizations, and industry stakeholders to guarantee that the forthcoming generation of civil engineering professionals is equipped with the requisite knowledge and skills to harness 4DP's potential [4]. In conclusion, the incorporation of 4DP into civil engineering carries immense potential to shape future infrastructures. As we confront and surmount the challenges and limitations of this technology, we lay the groundwork for a new epoch of adaptive, sustainable, and innovative civil engineering solutions. Embracing 4DP can allow us to construct a more intelligent, efficient, and resilient built environment, designed to serve the needs of our communities for generations to come.

Furthermore, 4DP is emerging as a transformative technology in the field of construction, promising revolutionary changes in how buildings and infrastructures are designed, constructed, and operated. This technology extends the capabilities of 3DP by introducing an additional time-based dimension, enabling printed structures to transform or self-assemble in response to external stimuli [1]. The potential of 4DP in construction is vast, yet its realization depends on advances across multiple research fronts. Existing literature provides numerous insights into these directions, which this paper aims to critically review. Recent studies highlight the advantages of 4DP in creating complex geometries that were previously challenging or even impossible to achieve with conventional construction techniques. 4DP facilitates the incorporation of smart materials that can adapt to changing environmental conditions, thereby enhancing the sustainability and resilience of built environments. However, these potential benefits are not without challenges. The selection of suitable materials for 4DP remains a crucial issue, with ongoing research exploring the adaptation of various materials, such as shape-memory alloys and polymers, hydrogels, and biopolymers, for construction applications [5,13]. Moreover, the scalability of 4DP for large-scale construction is another topic of active investigation. Studies are investigating the suitability of different printing technologies, such as Stereolithography (SLA) and Digital Light Processing (DLP), for large-scale 4DP [14]. This includes an examination of their feasibility for printing small and intricate components, which may not be possible with other methods.

Finally, the application of 4DP technology in civil engineering, though in its nascent stages, promises groundbreaking advances in the field. While 3DP technology offers the advantage of fabricating intricate geometric designs, 4DP takes it a notch higher by incorporating the element of transformation over time, facilitating self-assembly and response to environmental stimuli. This review provides a detailed examination of the current state of 4DP in civil engineering, presenting a critical analysis of existing research and discussing potential future developments. Our focus is not only to explore technological advancements but also to draw interconnections between them and shed light on how they might influence the future of civil engineering. While there are existing reviews that discuss 4DP technology, this review stands unique in its specific focus on the application and potential of 4DP in civil engineering. Unlike previous reviews, we delve deeper into the potential uses, benefits, and challenges of 4DP technology in the construction of large civil structures such as buildings, bridges, and dams. Moreover, our review provides an in-depth analysis of the methodological approaches used in this emerging field and offers a comprehensive summary and comparison of various studies. This approach allows us to provide a richer, more nuanced understanding of the state of 4DP technology in civil engineering and offer more targeted recommendations for future research and development in this field.

2. Methodology

This review is based on a comprehensive and systematic literature search conducted in scientific databases, including Scopus, Web of Science, and Google Scholar. We have also searched for additional relevant papers in the references of the articles found in the databases to ensure the review is exhaustive. The search was conducted using a combination of keywords and terms related to "4DP," "Civil Engineering," and "Construction." We have also included articles that discuss the potential of 4DP in civil engineering, even if they did not focus exclusively on this topic. The selection criteria were as follows:

- Articles published.
- Articles that discussed 4DP in the context of civil engineering and construction
- Both conceptual and empirical studies

Once we identified relevant articles, we analyzed them to extract information on the advantages, limitations, applications, and future directions of 4DP in civil engineering. The analysis involved both thematic synthesis and content analysis. Through this literature and rigorous methodological approach, we aimed to provide a comprehensive overview of the state of the art in 4DP in civil engineering, identify gaps in the current literature, and suggest directions for future research.

3. Scales and materials for 4D printing technology

One of the key advantages of 4DP of materials in civil engineering is that it allows for the creation of complex and sophisticated structures at a variety of scales. The technology can be used to print structures ranging from small, intricate components to large-scale buildings and infrastructure projects. To understand the advantages of 4DP see Fig. 1. At the smaller end of the scale, 4DP can be used to create micro-scale structures such as sensors, actuators, and microfluidic devices. These structures can be used in a variety of applications, from biomedical engineering to environmental monitoring and control. At the larger end of the scale, 4DP can be used to create full-scale buildings and infrastructure projects. For example, researchers at the Singapore Centre for 3DP have developed a technique for 4DP of concrete that can be used to create self-assembling buildings and structures [2,10,15]. These structures are designed to adapt to changing environmental conditions, such as earthquakes or sea level rise, and can be used in a variety of applications, from disaster relief to urban planning and design.

In addition to buildings and infrastructure projects, 4DP can also be used to create a wide range of other structures in civil engineering. These include bridges, tunnels, roads, and other transportation infrastructure, as well as dams, levees, and other water management structures. 4DP can also be used to create materials and structures for use in renewable energy applications, such as wind turbines and solar panels [10]. Overall, the potential applications of 4DP of materials in civil engineering are vast and varied, and the technology has the potential to transform many different aspects of the built environment. By enabling the creation of structures that are more efficient, sustainable, and adaptable, 4DP can help us build a better and more resilient built environment for the future.

In terms of the scales for printing, 4DP can be used to print structures at different levels of detail, ranging from micrometers to meters. The scale of the structure being printed will depend on the specific application and the capabilities of the printing technology being used. For example, at the micro-scale, researchers have used 4DP to create tiny sensors and actuators that can be embedded in medical devices or used for environmental monitoring. These structures may be only a few millimeters in size and require high precision printing techniques. At the larger end of the scale, researchers have used 4DP to create building components and structures, such as walls, floors, and columns. These structures may be several meters in size and require a larger-scale printing technology, such as a robotic arm or a gantry system [2,3,15].

It is worth noting that the size and complexity of the structure being printed will also impact the time and cost required for printing. Printing a complex structure, such as a building, may require thousands or even millions of individual printing steps, each of which can take several hours or more to complete. This means that 4DP of materials is still a relatively slow and expensive process and may not be suitable for all applications. As 4DP technology advances, it is expected that the process will become faster and more cost-effective, making it more suitable for a wider range of applications in civil engineering [2]. Continued research and development in the field of 4DP will likely lead to the discovery of new materials and printing techniques that can further expand the possibilities for this technology. In conclusion, 4DP offers immense potential in civil engineering, enabling the creation of adaptive, sustainable, and innovative structures at various scales. From small-scale sensors and actuators to large-scale buildings and infrastructure projects, 4DP has the potential to transform the way we design, construct, and maintain our built environment. As technology continues to develop and become more accessible, we can expect to see an increasing number of applications for 4DP in civil engineering, leading to a smarter, more efficient, and more resilient future for our communities.

3.1. 4D printing technologies and their potential for large-scale applications

The capabilities and constraints of various 4DP technologies greatly affect their potential for use in large-scale civil engineering applications. Currently, many 4DP technologies are adaptations of existing 3DP technologies, each with unique advantages and limitations that determine their suitability for different tasks. Stereolithography (SLA) and Digital Light Processing (DLP) are two such technologies, both of which utilize light to cure photosensitive polymers. SLA uses a laser to cure the material layer by layer, while DLP cures an entire layer simultaneously using a digital projector. These technologies can produce highly detailed and complex structures. However, they currently face challenges in scaling up due to factors such as the time and energy required for curing, and the need for a controlled environment to prevent premature curing. Fused Deposition Modeling (FDM), another common 3DP technology, has also been adapted for 4DP. FDM extrudes a filament of material that hardens upon cooling, allowing the fabrication of structures layer by layer. With FDM, it's possible to print with multiple materials in a single print job, making it a promising technology for 4DP of objects that respond to different stimuli [5,17].

Despite the current difficulty in scaling up 4DP technologies like SLA and DLP, these technologies can still play a crucial role in the creation of smaller components for civil engineering structures. For instance, they can be used to produce intricate, responsive elements that can be integrated into larger structures. This could include components designed to react to environmental stimuli, improving the overall adaptability and resilience of the structures. In terms of future potential for large-scale 4DP, ongoing research

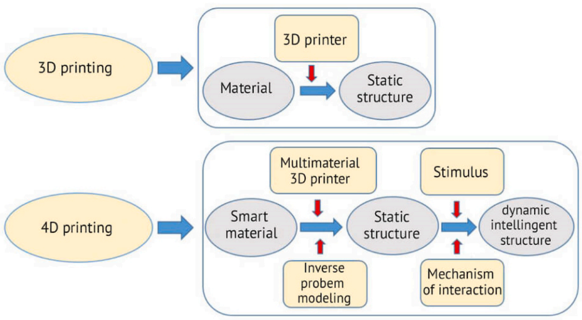

Fig. 1. Overview of the 4D printing process [16].

and development are key. Future advancements could lead to new materials and technologies that can be printed more efficiently at larger scales, expanding the potential applications of 4DP in civil engineering.

While the practical realization of 4D printed large-scale structures such as dams, bridges, and tunnels is still at its infancy, several innovative projects and research studies are currently exploring the potential of this technology. Moreover, the concept of smart dams built using 4D printed materials that can adapt to environmental changes and stress over time is being explored as a theoretical possibility. The vision here is to use 4DP to create dams that can autonomously adjust their structural properties in response to water flow variations or geological shifts, potentially enhancing their safety and longevity. Regarding tunnels, while no existing projects have realized full-scale 4D printed tunnels, the potential for implementing 4DP in tunnel construction is significant. By using materials that can adapt to ground movements, water ingress, and variations in pressure, 4D printed tunnel components could improve the safety and durability of tunnel structures, while reducing the need for manual maintenance. It's important to note, however, that these applications of 4DP in constructing dams, bridges, and tunnels are still largely theoretical or in the early stages of experimental research. Substantial further work will be necessary to validate these concepts in practice, and to overcome the considerable technical and regulatory challenges associated with large-scale 4DP in the civil engineering context.

3.2. Real-world instances of 4D printing in large civil structures

While the use of 4DP technology in large civil structures is still in its nascent stage, there have been significant research and development initiatives aiming to transform this vision into a reality. One of the most prominent examples of such efforts is the exploration of 4DP for constructing components of bridges. For example, a team of researchers has initiated the development of a 4D printed bridge that can adapt to various environmental stimuli. Using 4DP technology, this prototype bridge was designed with components that can change shape in response to varying load conditions. This adaptive behavior provides the bridge with enhanced structural integrity and resilience. In another instance, the concept of 4DP technology is being explored to create self-assembling tunnel components. These components are designed to assemble themselves into the complete tunnel structure under specific environmental conditions, significantly reducing the manual labor required and enhancing the speed and efficiency of tunnel construction. While these are still preliminary applications and largely confined to research and experimental settings, they showcase the potential for 4DP technology to be leveraged in constructing large civil structures. The evolution of these applications over time could eventually result in the widespread adoption of 4DP in the construction of dams, bridges, tunnels, and more [18–20].

Besides, 4DP holds immense potential for transforming the building construction industry by providing innovative solutions to longstanding challenges. To begin with, 4DP technology could substantially reduce the labor-intensive and time-consuming processes in conventional construction. The ability to fabricate complex, custom-made building elements directly from digital models could streamline construction processes, reducing lead times, and lowering costs. Additionally, 4DP could play a pivotal role in developing adaptive building elements capable of responding to environmental stimuli. For instance, smart façade elements that adjust their properties in response to changes in sunlight or temperature can improve building energy efficiency and create more comfortable indoor environments. Also, the potential of 4DP in fabricating structural components with built-in resilience, such as self-healing materials, could significantly enhance the safety and durability of built structures. Furthermore, 4DP opens up new possibilities for sustainable construction. The ability to print with a variety of materials, including eco-friendly alternatives such as bio-based materials, coupled with the inherent material efficiency of additive manufacturing processes, can contribute to the green building movement. Finally, 4DP can be instrumental in disaster mitigation and recovery. For instance, technology can facilitate the rapid construction of emergency shelters following natural disasters. In the future, with further advancements, it is even conceivable to have 4D printed buildings that can change their structure to withstand extreme weather events. While these potentials are exciting, it is important to acknowledge that there are still significant challenges to overcome, including technical issues related to material properties and 4DP processes, as well as regulatory and societal acceptance issues. Nevertheless, the ongoing research and development in the field are promising, indicating a bright future for 4DP in building construction [21,22].

3.3. Responsive construction materials in 4D printing

Four-dimensional (4D) printing, an evolution of three-dimensional (3D) printing, offers an innovative approach to manufacturing, enabling the creation of structures that can change and adapt over time in response to external stimuli. One of the keys to the success of 4DP is the use of smart materials, which respond to external factors such as temperature, moisture, light, or electric fields. This responsiveness allows 4D printed objects to adapt to their environment, opening up a range of potential applications, particularly in the field of civil engineering. At the forefront of responsive materials for 4DP are Shape Memory Polymers (SMPs) and Shape Memory Alloys (SMAs). SMPs are a type of smart material that can change their shape in response to heat or light. Similarly, SMAs can return to their pre-defined shape when heated. These materials hold promise for the construction of civil structures that can adapt to environmental changes, such as bridges that expand or contract in response to temperature fluctuations. Another promising avenue for research in 4DP materials for civil engineering is the development of smart concrete. Traditional concrete, while widely used in construction due to its strength and durability, is not inherently responsive. However, researchers are exploring ways to make concrete "smart." One such example is self-healing concrete, which contains bacteria that produce limestone when exposed to water, thereby healing any cracks that may appear over time. Another emerging technology is thermochromic concrete, which changes color in response to temperature changes, potentially providing a visual indicator of structural issues [1,23–25].

Hydrogels are another category of smart materials that can be used in 4DP. These substances can expand or contract significantly in response to changes in their environment, such as shifts in temperature or pH. This property could be used in civil engineering to create structures that adapt to environmental conditions, potentially improving their durability and lifespan. Although there have been exciting developments in the field of 4DP materials, significant challenges remain. The high cost and scarcity of smart materials can be a barrier to their widespread adoption. Furthermore, the complexity of designing and manufacturing 4D printed structures requires advanced computational models and precise control over material properties [2,26]. Despite these challenges, the potential benefits of 4DP in civil engineering – including increased resilience, adaptability, and longevity of structures – make it a worthwhile area of research. In conclusion, 4DP in civil engineering represents an exciting and promising field of study. As our understanding of smart materials continues to grow, so too will the potential applications of 4DP in construction.

While the potential of 4DP in civil engineering is vast, there remains a significant gap in understanding how to fully leverage these emerging technologies and materials. Fundamental research in materials science and engineering, computational design, and digital fabrication processes is needed to unlock the potential of 4DP. As advancements continue, it will be important to identify not only what is possible but also what is practical and sustainable for real-world civil engineering applications. One of the primary challenges for 4DP in construction is identifying materials that can respond in a robust and reliable manner to external stimuli. While Shape Memory Alloys (SMAs) and Polymers (SMPs) have shown significant promise in the lab, their performance in real-world environments, under varying conditions and over extended periods, remains largely untested. Furthermore, questions remain about the long-term durability of these materials, their resilience under different environmental conditions, and their compatibility with existing construction techniques and regulations [27]. In addition, there is a need to develop new methods for designing and modeling 4D printed structures. Currently, designing a 4D printed object requires a detailed understanding of both the geometry of the object and the behavior of the smart material under different conditions. This can be a complex and time-consuming process, requiring expertise in materials science, engineering, and computational design [28]. Moreover, there is a need to develop predictive models that can accurately simulate the behavior of 4D printed structures over time, under varying environmental conditions. Such models could help engineers optimize the design of 4D printed structures, ensuring that they respond appropriately to external stimuli.

Despite these challenges, the potential benefits of 4DP for civil engineering are significant. The ability to print structures that can adapt to their environment could dramatically improve the resilience and lifespan of civil infrastructure. For example, bridges could be designed to expand or contract in response to temperature changes, reducing the risk of thermal stress. Similarly, buildings could be designed to adapt to changing loads or environmental conditions, improving their energy efficiency and comfort. In the future, as our understanding of smart materials and 4DP techniques continues to evolve, it is likely that we will see an increasing number of applications in civil engineering. From adaptive buildings and self-healing roads to smart dams and bridges, the possibilities are vast. However, realizing these possibilities will require a concerted effort from researchers, engineers, and policymakers, to overcome the technical and regulatory challenges, and to ensure that these emerging technologies are developed in a sustainable and responsible manner.

3.4. Materials for 4D printing in civil engineering

Materials play a pivotal role in the application of 4DP technology in the field of civil engineering. The selection of materials not only determines the functionality and utility of the 4D printed structures but also their sustainability and environmental impact. At present, the market is predominantly filled with petroleum-based substrates that outperform most biological substrates in terms of cost-effectiveness and mechanical properties. However, these petroleum-based materials carry significant environmental implications, primarily due to their non-renewable nature and detrimental effect on the ecosystem. Given the rising demand for sustainable solutions, there's a growing interest in the development and use of eco-friendly alternatives. These alternatives chiefly encompass natural fibers and other bio-based materials. Besides potentially reducing the ecological impact of 4DP practices in civil engineering, these materials present opportunities to produce functionally intricate printed structures.

Natural fibers, including cellulose, hemp, and flax, possess multiple desirable properties that make them an attractive option for 4DP. Some of these properties include high strength-to-weight ratios, renewability, and biodegradability. However, using these fibers in 4DP is not without challenges. One primary challenge is their lack of stimulus-responsive properties, which are characteristic of 4D printed structures. Recent research has attempted to overcome this hurdle by functionalizing natural fibers with smart materials capable of responding to various environmental stimuli. For instance, integrating natural fibers with shape-memory polymers has been studied. These polymers can be programmed to change their shapes in response to a specific trigger, such as heat. As a result, the fibers serve a dual purpose: they reinforce the structure and provide the desired 4D functionality [29,30]. Other bio-based materials, such as alginate and lignin, have also been the focus of recent research for their potential application in 4DP. Alginate, a biopolymer found in seaweed, can be used to produce hydrogels responsive to changes in humidity and temperature. On the other hand, lignin, a by-product of the paper and pulp industry, exhibits shape-memory properties when combined with certain types of polymers. These materials show that bio-based alternatives can contribute significantly to the 4DP sector. Their use can lead to environmentally friendly construction practices while adding functional complexity to the printed structures. However, the current high costs and limited availability of these materials pose a considerable challenge to their widespread application in the industry. It is important to highlight that research and development efforts are ongoing to reduce these costs and increase the availability of sustainable 4DP materials. With the increasing emphasis on sustainability in civil engineering and construction, the exploration and development of bio-based materials for 4DP promise an exciting avenue of future research [31,32].

Notwithstanding the challenges, the potential benefits offered by these bio-based materials – their renewability, biodegradability, and potential to create functionally complex structures – position them as strong candidates for the future of 4DP in civil engineering. In conclusion, the materials used in 4DP, whether petroleum-based or bio-based, significantly influence the properties, capabilities, and environmental impact of the resulting structures. This realization underpins the urgent need for continued research and development in this area to identify and exploit new, sustainable materials that can further enhance the effectiveness and sustainability of 4DP in civil engineering [33].

3.5. Materials used in 4D printing for construction: opportunities and challenges

The material choice in 4DP, particularly in the context of construction, plays a pivotal role due to the specific needs of adaptability, durability, and performance. The materials utilized can be broadly classified into two categories, smart materials, and conventional construction materials. Smart materials, such as Shape Memory Alloys (SMAs), Shape Memory Polymers (SMPs), Hydrogels, and dielectric elastomers, display a high degree of adaptability in response to external stimuli like heat, light, moisture, or electrical signals. SMAs and SMPs are especially noteworthy for their ability to 'remember' and return to their original shape after deformation. This property is highly beneficial for the construction of structures requiring dynamic adaptability. However, these materials are relatively expensive and may not be feasible for large-scale construction yet. Hydrogels are an exciting prospect for 4DP in construction due to their responsiveness to changes in moisture and temperature. Yet, the use of hydrogels in construction faces hurdles due to their lower structural strength compared to traditional construction materials, limiting their applications to non-load-bearing structures. Conventional construction materials, such as concrete and metals, are also being explored for use in 4DP. For instance, the research into self-healing concrete and programmable cement presents intriguing possibilities for 4DP. These materials can potentially self-repair cracks, enhancing longevity and reducing maintenance costs. However, making these materials compatible with 4DP processes remains a significant challenge due to the technical difficulties in controlling their behavior [34–36].

3.6. Applications and future potential of 4D printing in construction

The potential applications of 4DP in construction are vast, as they encompass both architectural and structural elements. 4D printed building components can adapt to environmental conditions, self-assemble, and potentially even self-repair, making them ideal for creating structures that are resilient, sustainable, and efficient. For example, 4DP can be used to create adaptive building facades that respond to changing environmental conditions, such as sunlight and temperature. These "smart facades" can open or close to regulate interior temperatures, reducing the need for artificial heating or cooling and thus improving energy efficiency. Structurally, 4DP can be used to manufacture self-assembling components. This could significantly streamline the construction process, reducing the need for manual labor and enabling more complex and precise structures. Research into 4D printed concrete has suggested its use for creating more sustainable construction methods. This involves embedding 4D properties into the concrete to allow it to adapt and respond to its environment over time. This could pave the way for self-healing structures that can automatically fix cracks and faults, thus improving safety and longevity while reducing maintenance costs. Despite its promise, the implementation of 4DP in construction also presents significant challenges. The complex design process, the need for new construction practices, the high cost of smart materials, and the technological limitations related to scale and speed all pose hurdles. However, as research continues and the technology matures, 4DP could revolutionize the construction industry [37–39].

4. Characteristics of 4D printing materials

The advent of 4DP technology has opened up avenues for the application of smart materials in a wide array of sectors. With the unique feature of being able to alter their physical properties or shape over time in response to external stimuli such as temperature, moisture, light, or even pH levels, these materials play a critical role in the transformative nature of 4D printed objects. Hydrogels, shape-memory polymers (SMPs), and light-activated polymers are some of the main categories of materials employed in 4DP. Hydrogels have a high-water content, and their ability to swell or shrink in response to changes in their environment makes them a

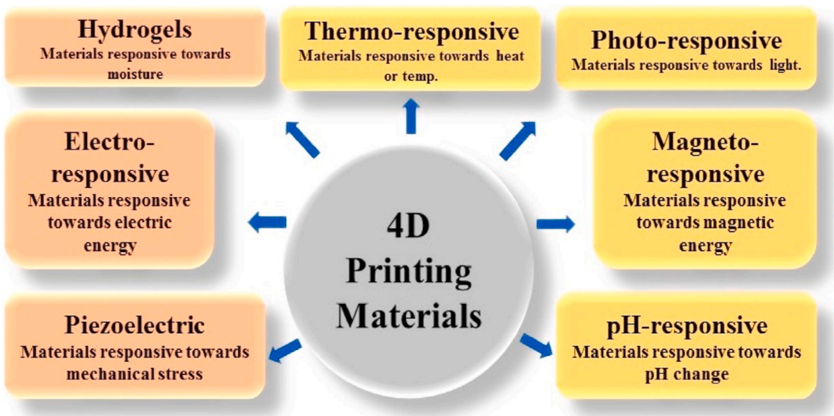

Fig. 2. Types of materials used for 4D printing [35].

popular choice for 4DP applications [1,23,40].

SMPs, on the other hand, are noted for their ability to revert to a pre-determined shape when subjected to a particular stimulus, usually heat. This characteristic makes them an ideal choice for applications where the 4D printed object needs to maintain one shape under certain conditions and transform into another shape when these conditions change. Light-activated polymers undergo deformation when exposed to specific wavelengths of light, making them suitable for precision applications. An example of this is the use of these materials in 4DP of medical devices where precise control over shape transformation is critical. Bio-derived materials, like cellulose and other natural fibers, are also gaining attention in the field of 4DP due to their environmental sustainability and potential for innovative applications. These materials are often combined with synthetic polymers to develop composites that leverage the beneficial properties of both types of materials [41,42]. Each of these materials has its strengths and weaknesses, which determine their suitability for different applications. As such, choosing the right material for a specific 4DP application is a complex process that requires careful consideration of the material's response to stimuli, mechanical properties, durability, and printability, among other factors. Fig. 2 graphically illustrates various smart materials that are commonly employed in 4D printing. Among these, pH-responsive materials, especially polymers, hold a significant place due to their unique capability to alter their shape and volume in response to variations in pH value. pH-responsive polymers, such as polyelectrolytes, are integrated with ionizable side groups that can donate or receive protons, depending on the shift in pH. This process triggers structural deformation. The release of a proton causes an expansion in the polymer chain due to electrostatic repulsion, whereas the acceptance of a proton neutralizes the structure. Polyelectrolytes are further characterized by the presence of functional groups - polycations or polybases (like ammonium salt) and polyanions or polyacids (such as carboxyl or sulphonic groups). The ionizable side chains, i.e., polyanions or polyacids, release protons at higher pH levels and accept them at lower pH values. Simultaneously, the functional groups, i.e., polycations or polybases, behave oppositely, releasing protons at lower pH and accepting them at higher pH values. The characteristic pH-responsiveness of these materials has been found diverse applications, including drug delivery systems, soft robotics, actuators, valves, biocatalysts, and colloid stabilization. This categorization of materials, as shown in Fig. 2, provides a broader perspective on their potential and utilization in the 4D printing technology realm.

4.1. Post-processing of 4D printed parts

Post-processing is a critical aspect of the 4DP process that significantly impacts the final performance and quality of the produced parts. It includes several steps that are undertaken after the printing process to enhance the material's properties and improve its aesthetics, dimensional accuracy, and functionality. Typical post-processing steps in 4DP might include:

- ***Cleaning:*** After the printing process, the printed object is cleaned to remove any remaining support material or residue. This is typically done using chemical solvents or by mechanical means [43].
- ***Curing:*** In some 4DP applications, especially those using photo-reactive resins, the printed parts require UV curing to fully solidify the material and enhance its mechanical properties [44].
- ***Heat Treatment:*** Heat treatment, also known as annealing or thermal conditioning, is often used in 4DP to program the printed parts' shape memory behavior. During this process, the printed object is heated to a specific temperature and held in a desired shape. Upon cooling, the object retains this shape until it is triggered to transform using an external stimulus [3].
- ***Finishing:*** This process enhances the aesthetics and functional performance of the printed parts. Finishing processes may include sanding to smooth the surface, painting for aesthetic appeal, or coating to improve the object's hardness or resistance to environmental factors [45].

Proper post-processing can improve the overall quality of 4D printed objects and is an integral part of the 4DP workflow that warrants careful consideration in the design and fabrication stages.

4.2. Key components of 4D printing for civil engineering

Integrating 4DP into civil engineering has the potential to transform infrastructure design, construction, and maintenance. The critical components of 4DP in civil engineering include material selection, design, printing process, and external stimuli.

- ***Material Selection: Detailed Analysis*:** SMPs can revert to their original form after deformation when exposed to an external stimulus like heat, making them suitable for structures needing to adapt to changing loads or recover from natural disasters. Hydrogels change their size and shape in response to environmental factors such as humidity or temperature, making them useful for moisture regulation or adapting to changing conditions. Stimuli-responsive composites, composed of two or more distinct constituents, enable engineers to create adaptive materials tailored to specific applications by combining materials with unique responses to external stimuli [2,3,10,15].
- ***Design: Cutting-Edge Methodologies and Tools*:** Topology optimization is a computational design method that helps engineers identify optimal material distribution within a structure to achieve performance objectives while minimizing material usage. Generative design uses algorithms and computational tools to generate multiple design solutions based on predefined criteria, leading to innovative structures that leverage the unique properties of 4D-printed materials. 4DP technologies are bringing about a paradigm shift in the construction industry. The ability to fabricate structures that are not only complex in shape but also display smart behavior - transforming in response to environmental stimuli - is opening new possibilities in design and engineering. For

instance, the concept of self-assembling structures, made possible by 4DP, is one such development. One notable example is the work of Tibbits., S et al. [1], where a 4D printed structure made of a composite material was able to fold itself into a predefined shape when submerged in water. This smart behavior was due to the use of a hydro-responsive material, which expands or contracts in response to changes in water content. Such materials, when designed and 4D printed in a precise manner, can result in complex shape transformations that can be pre-programmed during the design stage itself. The implications of such technology in civil engineering are significant - for instance, components or entire structures could be shipped flat and then self-assemble on-site, reducing transport costs and assembly time. However, while these developments are promising, it's crucial to consider the challenges and limitations. The material properties necessary for 4D transformations are often a trade-off with other important aspects such as strength, durability, and resistance to environmental degradation. In addition, the technology required for large-scale 4DP is still under development, and the costs associated with it can be prohibitive. Therefore, while 4DP offers exciting possibilities for the future of civil engineering, it is vital to continue research into overcoming these challenges [3,15,46].

- ***Printing Process: Advanced Techniques and Challenges***: Stereolithography (SLA) uses a light source to selectively cure liquid photopolymer resin, layer by layer. Although it can produce high-resolution structures, scaling for large civil engineering projects remains a challenge. Fused deposition modeling (FDM) involves extruding a thermoplastic filament layer by layer to build a structure. While FDM works with various materials, achieving high-resolution and precision in large-scale applications is challenging. Selective laser sintering (SLS) fuses powdered materials layer by layer using a high-powered laser, offering excellent material compatibility and high-resolution output. However, scalability and cost for large civil engineering projects need to be addressed, see Fig. 4 [1,2,10].

Figs. 3 and 4 illustrate the basic principles of several 3D and 4DP techniques, including Stereolithography (SLA), Digital Light Processing (DLP), and Fused Deposition Modeling (FDM), respectively. These techniques use a variety of materials suited for different applications in civil engineering. For instance, SLA (Fig. 3) commonly employs photopolymer resins that solidify under light exposure, making it suitable for creating highly detailed, small-scale models or components. DLP (Fig. 4) uses a similar mechanism but can achieve faster print times at the expense of some detail.

Fig. 5 illustrates the fundamental components and operational mechanisms of two primary 4D printing processes: Stereolithography (SLA) and Digital Light Processing (DLP). In this figure, the SLA process is demonstrated using a bottom-up approach, wherein the object is constructed starting from the bottom and moving upwards. On the other hand, DLP is depicted employing a top-down strategy, whereby the platform rises as the object is formed discerningly. Both these methods have their unique benefits and cater to specific project requirements. Their understanding is paramount for realizing the potential applications and versatility of 4D printing, especially in the realm of civil engineering.

Moving forward, Fig. 6 provides an exhaustive outline of the process parameters associated with three distinct printing techniques

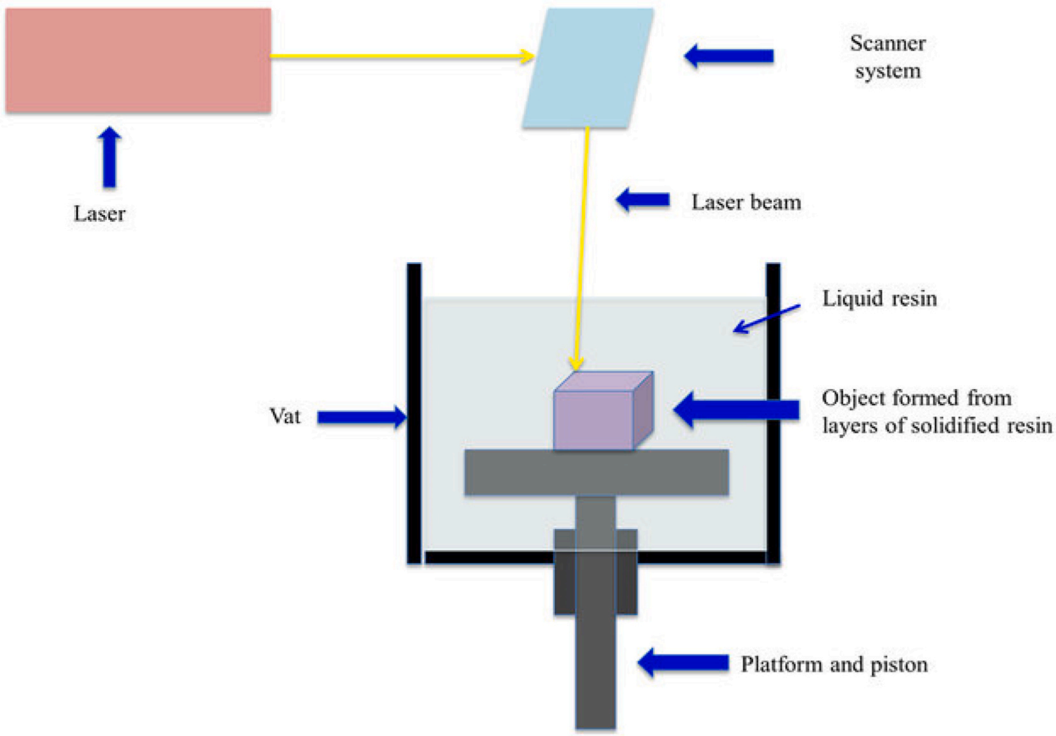

Fig. 3. Schematic of Stereolithography (SLA) technology, 3DP process [47].

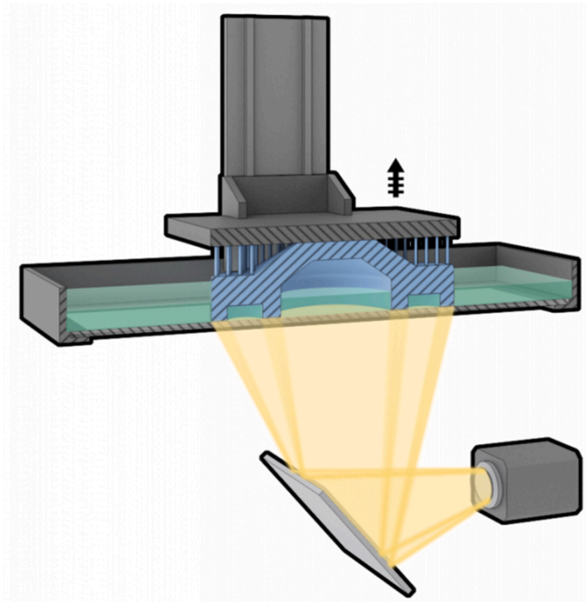

Fig. 4. Schematic of digital light processing (DLP) technology [48].

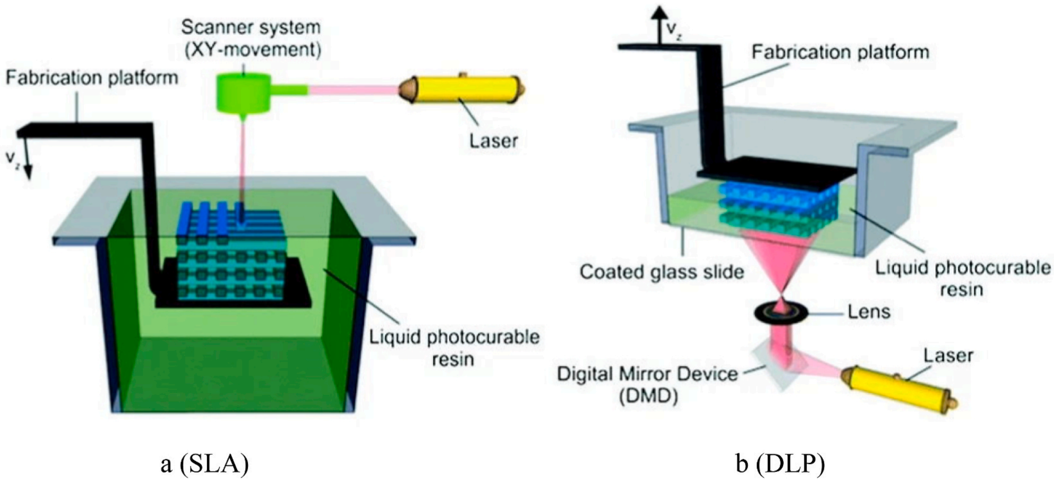

Fig. 5. Scheme of bottom-up stereolithography (SLA) and top-down digital light processing (DLP) setups [49].

employed in 4D printing: Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA). Each methodology is delineated with its respective process parameters, allowing readers a comparative analysis of the different techniques. Such a juxtaposition is instrumental in grasping the diverse operational procedures inherent to 4D printing. It also sheds light on their practical implications, specifically in the civil engineering context.

- ***External Stimuli: Customizing Responses and Applications***: Temperature-responsive 4D-printed structures can expand, contract, or change shape, enabling adaptive building facades or structures that respond to seasonal variations. Moisture-responsive materials can adapt to humidity or precipitation changes, with potential applications in flood barriers, moisture-regulating components, and structures adapting to changing ground conditions. Load-responsive 4D-printed structures can redistribute forces and adapt to varying loads, enhancing structural resilience and safety, particularly in earthquake-resistant structures or infrastructure accommodating fluctuating demands. Developing new smart materials and improving existing ones will allow engineers to design structures that adapt better to changing conditions, improve safety and resilience, and promote sustainable construction practices. Advanced computational techniques like topology optimization and generative design are essential for creating innovative and efficient 4D-printed structures. Scaling up 4DP technologies and understanding the relationship between external stimuli and adaptive behavior are crucial for tailoring materials to specific civil engineering applications. By investigating how structures

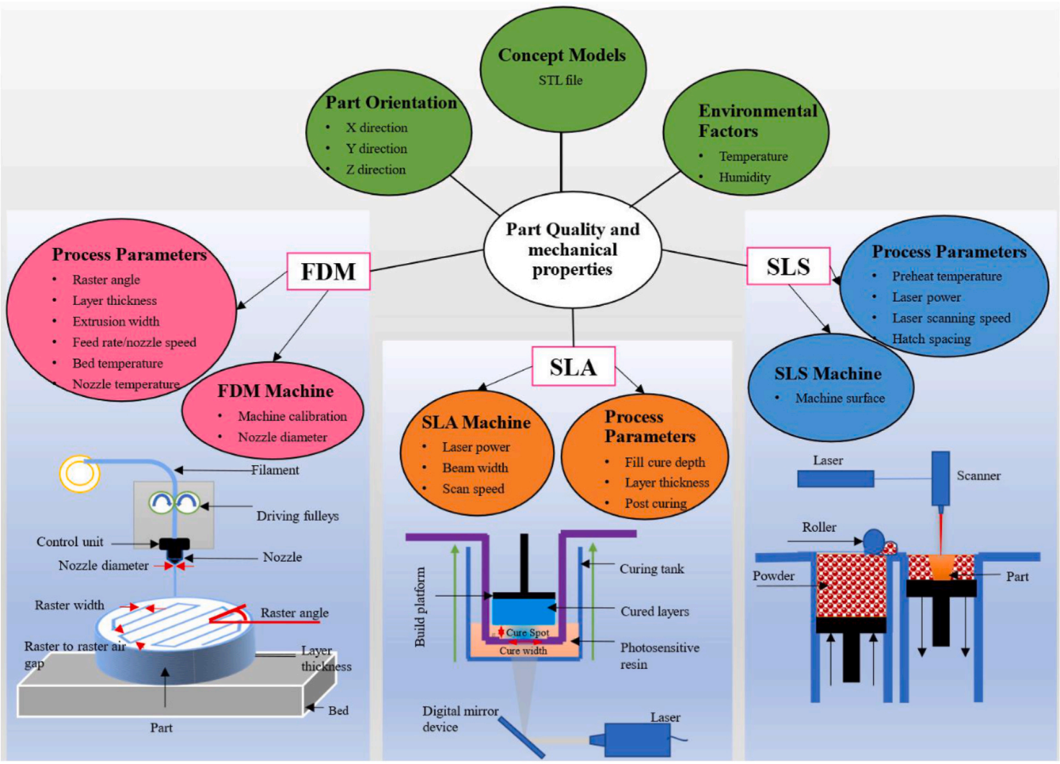

Fig. 6. Overview of the process parameters of three different print methods (i.e., FDM, SLS, and SLA) [45].

respond to temperature, moisture, and load, engineers can design infrastructure components that are more adaptive, resilient, and efficient. By addressing the challenges and limitations of 4DP, we pave the way for a future where our built environment is smarter, more efficient, and more resilient than ever before [2,3,10,15].

As the field of 4DP for civil engineering continues to advance, interdisciplinary collaboration between material scientists, engineers, architects, and urban planners will be essential in ensuring the successful implementation of these technologies in real-world applications. Moreover, the regulatory landscape must adapt to accommodate and support the development and deployment of 4D printed infrastructure components, addressing issues such as safety, standardization, and sustainability. Education and training programs must also evolve to prepare the next generation of civil engineers and designers for the challenges and opportunities presented by 4DP. Integrating topics such as material science, computational design, and additive manufacturing into civil engineering curricula will help to equip future professionals with the knowledge and skills needed to harness the potential of 4DP in their work. Furthermore, public awareness and acceptance of 4D printed infrastructure will play a crucial role in the widespread adoption of this technology. Communicating the benefits and addressing potential concerns related to 4DP will be vital in ensuring that communities are receptive to and supportive of these innovative solutions [1,10,15]. Ultimately, by continuing to research, develop, and refine the key components of 4DP for civil engineering, we can create a future where our infrastructure is not only more responsive and resilient but also more sustainable and efficient. As a result, we can enhance the quality of life for people in urban and rural environments alike, fostering more adaptable and dynamic built environments for generations to come. Table 1 offers a summary of pivotal studies in the realm of 4DP technology, focusing on civil engineering. The table outlines the authors, year of publication, the technology utilized,

Table 1
Summary of key literature on 4DP technology in civil engineering.

Author(s)	Year	Key Findings	Relevance to 4DP in Civil Engineering
Spiegel, C. A. et al. [50]	2022	Demonstrated the use of shape memory polymers in 4D printing, allowing structures to change shape over time.	This could be crucial in the development of adaptable infrastructure.
Manshor, M. R. et al. [51]	2023	Explored the potential of 4DP to create self-healing structures, reducing maintenance costs.	This could significantly enhance the durability and lifespan of civil engineering structures.
Ram Kishore, S. et al. [9]	2023	Showed that 4DP can potentially reduce waste during the construction process due to its additive manufacturing nature.	This directly relates to sustainable construction, a key concern in contemporary civil engineering.
Vatanparast, S. et al. [52]	2023	Proposed a novel 4D printing method that allows the precise control of deformation, leading to highly adaptable structures.	This could have a major impact on design flexibility in civil engineering.

material type, application, and the key findings of each study. A separate section within the table highlights ground-breaking research outcomes in civil engineering using 3DP technology. This summary provides readers with a comprehensive overview of the state-of-the-art in 4DP for civil engineering.

- ***Material Strength and Structural Rigidity in 4DP***: High-rise construction, due to its inherent complexity, presents a unique set of challenges and requirements in terms of the strength, flexibility, and durability of the materials used. 4DP, while showing promise in several other applications, is still in its nascent stage when it comes to high-rise building construction. This is mainly due to the rigorous structural demands that must be met in such projects. In the following section, we delve into the specific material requirements for 4DP in high-rise constructions and discuss the possible thermophysical and chemical changes that must be considered. Extrusion-based printing, a commonly used technique in 3D and 4DP, utilizes a specific consistency of the material that allows it to be smoothly dispensed and then quickly harden upon exposure to air. However, for high-rise construction, the transition from a soft, extrudable state to a rigid, durable state is of critical importance and must be carefully controlled. Too rapid a transition can result in structural instabilities, while a transition that is too slow can hamper the construction process. The balance between these extremes is largely governed by the thermophysical and chemical properties of the material used. Materials used in 4DP for high-rise construction must exhibit exceptional strength and durability to withstand the loads they will be subjected to. However, they also need to retain a certain level of flexibility and adaptability to accommodate building movements caused by factors such as wind, seismic activity, and thermal expansion. Furthermore, the materials need to maintain their structural integrity over a long period, under various environmental conditions [1,21].

Various researches have been exploring the use of composite materials, often with a mixture of concrete, polymers, and certain types of fibers, for 4DP in high-rise construction. These composites, while providing the necessary strength and rigidity, are designed to undergo specific chemical reactions that allow them to harden at a controlled rate upon being extruded. However, understanding and controlling the complex thermophysical and chemical changes these materials undergo during the printing process remains a challenge. Key factors that need to be considered include the heat generation and dissipation during the hardening process, the chemical interactions between different material components, and the impact of these factors on the overall structural integrity of the printed structure. Therefore, further research is required to optimize the composition and processing parameters of these materials to make them suitable for high-rise construction. Innovative solutions such as the use of smart materials that can adapt to environmental changes, or materials with built-in self-healing properties, could also play a significant role in advancing the application of 4DP in high-rise construction [53,54]. In conclusion, while the potential of 4DP in high-rise construction is immense, careful consideration of the material characteristics and the control of thermophysical and chemical changes during the printing process are crucial for successful implementation. The development of new materials and printing techniques that can meet these stringent requirements will be a key focus area in future research in this field.

5. Quantitative aspects of 4D printing in construction

The potential of 4DP in civil engineering is inextricably linked to an understanding of the quantitative dynamics underlying the technology. Any evaluation of a construction technology needs to consider not just the technical possibilities it offers, but also the costs associated with its adoption. For 4DP, these costs are most effectively understood through the lenses of energy consumption, direct and indirect costs, and time consumption.

- ***Energy Consumption:*** Energy consumption in 4DP processes can be influenced by a range of factors, from the type of materials being used to the complexity of the components being printed. Each type of 4DP technology, be it Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Stereolithography (SLA), or others, comes with its unique energy requirements. Some processes may demand high energy levels for particle fusion, while others, focusing on material extrusion, could involve lower energy expenditures. It is also worth noting that the specific characteristics of the material being printed can also significantly impact the amount of energy required for the 4DP process. The energy consumption of these processes needs to be evaluated in relation to the energy costs and environmental implications they entail [41].
- ***Cost Considerations***: When assessing the cost aspects of 4DP in construction, we need to factor in the cost of the 4D printer itself, the cost of materials, and the ongoing operational costs. The initial cost of 4D printers can vary greatly depending on their capabilities and the scale of operations they support. Further, material costs, dictated by the type and quality of the material chosen, also form a substantial part of the overall cost. Finally, operational costs, which include energy costs and maintenance costs, round out the financial investment required for 4DP in construction. Given the potential advantages of 4D printed structures in terms of their adaptive and self-assembly capabilities, these costs must be compared against the potential long-term savings and benefits that the technology can deliver [55].
- ***Time Consumption:*** Another crucial factor is the time consumption of the 4DP process. The time factor is twofold, involving not just the time required for printing but also the subsequent time necessary for the printed structures to transform or self-assemble. The time consumption of the 4DP process can be influenced by the type of technology being used, the complexity of the structures being printed, and the characteristics of the materials. For instance, some materials may require a longer period for transformation due to their inherent properties [21].

In summary, understanding the quantitative dynamics of 4DP in construction is key to assessing its viability and potential for widespread adoption. These factors underline the need for further research and development aimed at enhancing the efficiency, affordability, and scalability of 4DP technologies in the construction industry.

5.1. Opportunities in civil engineering with 4D printing

4D printing technology presents numerous opportunities for innovation, efficiency, and sustainability in civil engineering [18]. These opportunities include adaptive infrastructure, sustainable construction, self-assembling and self-healing structures, enhanced design possibilities, improved accessibility and affordability, smart transportation systems, energy-efficient infrastructure, disaster-resistant structures, urban planning and development, and workforce development and education.

- ***Adaptive Infrastructure:*** 4DP enables the creation of adaptive infrastructure that responds to external stimuli such as temperature, moisture, and load [1], leading to increased safety, resilience, and efficiency in the built environment, especially during natural disasters or extreme weather events.
- ***Sustainable Construction:*** 4DP contributes to sustainable construction practices by allowing for the design of eco-friendly structures that minimize waste, reduce energy consumption, and facilitate disassembly and recycling [2].
- ***Self-Assembling and Self-Healing Structures:*** The potential for 4DP to create self-assembling and self-healing structures can revolutionize the construction process, reduce maintenance needs, and extend the service life of infrastructure components [56].
- ***Enhanced Design Possibilities:*** 4DP opens new design possibilities, enabling the creation of complex geometric structures that are functional, efficient, aesthetically striking, and innovative [14].
- ***Improved Accessibility and Affordability:*** 4DP can democratize access to advanced construction technologies, making it more feasible and cost-effective to deploy cutting-edge infrastructure solutions in remote or underserved areas [57].
- ***Smart Transportation Systems:*** 4DP can transform transportation infrastructure by enabling the development of adaptive, intelligent systems that respond to real-time conditions [58].
- ***Energy-Efficient Infrastructure:*** The use of 4D-printed materials in civil engineering can contribute to more energy-efficient infrastructure, such as building envelopes and facades designed to react to sunlight and temperature variations, optimizing the balance between natural light and thermal comfort while reducing energy consumption [59].
- ***Disaster-Resistant Structures:*** 4DP technology can play a crucial role in developing disaster-resistant structures by designing structures that adapt and respond to extreme forces, such as earthquakes, hurricanes, or floods, improving infrastructure resilience and safety [60].
- ***Urban Planning and Development:*** The integration of 4DP into urban planning and development can lead to more efficient, sustainable, and adaptable cities, leveraging the adaptive capabilities of 4D-printed materials to design flexible and dynamic urban spaces that can easily adapt to changing demographics, environmental conditions, and evolving community needs [61].
- ***Workforce Development and Education:*** The emergence of 4DP in civil engineering presents opportunities for workforce development and education, necessitating collaboration between educational institutions, professional organizations, and industry stakeholders to develop training programs and curricula that prepare the next generation of civil engineers to work with 4DP technologies and materials [23].

In conclusion, the potential applications and opportunities presented by 4DP in civil engineering extend far beyond what we have discussed here. By embracing this innovative technology and exploring its many possible uses, we can revolutionize the way we approach the design, construction, and maintenance of our infrastructure, ultimately creating a more sustainable, efficient, and resilient built environment for generations to come [23]. By harnessing the power of 4DP to create adaptive, sustainable, and innovative structures, we can envision a future where our built environment is smarter, more efficient, and more resilient, ultimately improving the quality of life for people around the world [1,58].

6. Environmental impact and sustainability of 4D printing in civil engineering

4D printing, a revolutionary concept that incorporates time as an additional dimension to 3D printed structures, enabling them to transform over time in response to external stimuli, has potential applications in many sectors, including civil engineering. However, just like any new technology, it is essential to assess its environmental impact and sustainability. This section aims to examine the environmental implications, recyclability, and sustainability of 4DP technology in the realm of civil engineering. The environmental impact of 4DP can be categorized under two main themes: the consumption of resources (including materials and energy) and the emission of pollutants (including waste generation). As with any production process, 4DP relies on a range of resources, most notably energy and printing materials. The energy consumption in the 4DP process can vary significantly depending on the specific printing technology employed and the complexity of the printed object [8]. In general, however, 4DP technologies tend to be energy intensive. Efforts to improve the energy efficiency of 4DP processes, therefore, constitute a crucial aspect of enhancing their environmental performance.

The materials used in 4DP, on the other hand, have a significant environmental impact due to their extraction, processing, and disposal. Currently, most 4DP applications employ polymer-based materials, whose production and disposal can have considerable environmental impacts. Several studies have shown that replacing these traditional materials with more sustainable alternatives, such as bio-based polymers or recycled materials, can substantially mitigate the environmental footprint of 4DP. In terms of waste generation, 4DP can potentially contribute to reducing construction waste since it allows for precise manufacturing, reducing the need for material overuse and offcuts. Moreover, the possibility of recycling or reusing the materials used in 4DP processes represents a significant opportunity for improving their environmental performance. Recent advancements in material science have made it possible to develop 4D printed objects using recyclable or even biodegradable materials [7,62]. As for sustainability, it refers to a broader concept that encompasses not only environmental but also social and economic aspects. From a sustainability standpoint, 4DP holds great promise due to its potential to revolutionize the construction process, leading to safer, faster, and more cost-effective projects. In this context, 4DP can contribute to achieving several of the United Nations' Sustainable Development Goals (SDGs), such as SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) [63]. However, while the potential benefits are significant, it is important to note that the sustainability of 4DP technologies ultimately depends on how they are implemented. Care must be taken to ensure that the introduction and proliferation of these technologies do not lead to unintended social or economic consequences, such as job losses in traditional construction sectors or exacerbation of social inequalities. Hence, a comprehensive sustainability assessment of 4DP technologies, considering all these dimensions, is paramount for guiding their development and deployment in a truly sustainable manner. In conclusion, while 4DP offers exciting prospects for the civil engineering sector, it is not without its environmental and sustainability challenges. Addressing these challenges requires concerted efforts in technological innovation, policymaking, and sustainability assessment, with the goal of maximizing the benefits of 4DP technologies while minimizing their potential negative impacts.

7. Challenges and future directions in civil engineering with 4D printing

Incorporating 4DP technology into the field of civil engineering involves surmounting numerous challenges. Notably, the most formidable hurdle resides in scaling up the 4DP process for large civil structures. While laboratory results present a promising future for this technology, its real-world implementation for large-scale applications necessitates overcoming multiple obstacles in technology, materials science, and financial feasibility. The core technology behind 4DP, much like its 3D counterpart, has mainly been explored in the creation of small-scale objects or prototypes. This limited scope is largely due to the technological constraints of the printers themselves. The transition from fabricating small, detailed parts to the large-scale components required in civil engineering is not a straightforward process. The complexity of construction-scale 4DP involves not only significantly larger machines and production facilities but also the logistics of assembling large-scale parts, the reliability of large print jobs, and the integration of such technologies into current construction processes [2,3].

Moreover, the existing materials for 4DP, although displaying remarkable characteristics in the lab, may not retain these attributes when used in larger quantities or structures. Ensuring the structural integrity and programmability of 4D printed structures at large scales is a challenge that requires rigorous testing and development. As the scale of a printed part increases, maintaining uniform heat distribution, consistent material properties, and precise control over shape change becomes increasingly difficult. Financial viability is another challenge that hinders the immediate adoption of large-scale 4DP in civil engineering. The cost associated with the procurement and maintenance of large 4D printers, coupled with the high price of smart materials, can be substantial. Furthermore, the development of new materials suitable for large-scale printing, which ensures structural integrity and programmability, demands significant investment in research and development [64,65]. In conclusion, although the future of 4DP in civil engineering holds great potential, the immediate challenge lies in overcoming the hurdles associated with scaling up the technology for practical, large-scale applications. This will require concerted effort across multiple disciplines, including materials science, engineering, and economics. While 4DP offers numerous opportunities for innovation and advancement in civil engineering, there are several challenges that must be addressed to fully realize its potential. In this section, we will discuss some of the most pressing challenges and explore future directions for research and development in 4DP for civil engineering [2].

- ***Material Development and Standardization:*** One of the major challenges in 4DP for civil engineering is the development and standardization of materials. The current range of smart materials with shape-shifting properties is limited, and their long-term performance under various environmental conditions and loading scenarios is not yet fully understood. Addressing this challenge will require extensive research into the development of new materials with improved mechanical properties, durability, and environmental resistance, as well as the establishment of material standards and guidelines for their use in civil engineering applications [3].
- ***Scalability and Construction Processes:*** Another challenge is the scalability of 4DP technologies and the adaptation of construction processes to accommodate these new materials and techniques. While small-scale prototypes and demonstrations have shown promise, scaling up 4DP for large civil engineering projects remains a significant challenge. Future research and development efforts should focus on the development of large-scale 4DP equipment, as well as the adaptation of construction processes to incorporate 4D-printed components efficiently and safely [66].
- ***Design Tools and Methods:*** The design of 4D-printed structures presents its own set of challenges, as traditional design tools and methods may not be suitable for fully exploiting the unique properties of smart materials. Future work should focus on the development of advanced design tools and methods that can account for the dynamic behavior of 4D-printed structures and optimize their performance. This may include the integration of machine learning and artificial intelligence techniques, as well as the development of new simulation models and optimization algorithms [13].
- ***Regulatory Frameworks and Building Codes:*** As 4DP gains traction in civil engineering, there will be a need to develop appropriate regulatory frameworks and building codes that account for the unique properties and behaviors of 4D-printed structures. This will involve collaboration between researchers, industry professionals, and policymakers to establish guidelines and standards that ensure the safe and effective implementation of 4DP technologies in the built environment [2].

- ***Economic Viability and Market Adoption:*** The economic viability of 4DP for civil engineering applications is another challenge that must be addressed. The initial costs of 4DP technologies and materials may be high, and the return on investment may be uncertain. To promote widespread market adoption, it will be crucial to demonstrate the long-term benefits and cost savings associated with 4DP, such as reduced maintenance costs, improved structural performance, and increased sustainability [3].
- ***Education and Workforce Development:*** The successful integration of 4DP into civil engineering practice will require a workforce with the necessary skills and knowledge to design, construct, and maintain 4D-printed infrastructure. This will necessitate the development of educational programs and training initiatives to equip the next generation of civil engineers with the tools and expertise required to work with 4DP technologies and materials [67].

Addressing these challenges and advancing the field of 4DP in civil engineering will require multidisciplinary collaboration, investment in research and development, and a willingness to embrace new ideas and approaches. By overcoming these hurdles, we can unlock the full potential of 4DP to revolutionize the design, construction, and maintenance of our infrastructure, creating a more sustainable, efficient, and resilient built environment for the future. To fully realize the potential of 4DP in civil engineering and overcome the challenges previously discussed, several strategies should be pursued to foster collaboration and innovation within the industry. These strategies include interdisciplinary research, public-private partnerships, investments in research and development, and international collaboration. Despite the promising advancements and potential of 4DP technology in the construction industry, there are still several challenges and areas of uncertainty that need to be addressed. One such area is the standardization of 4DP processes and protocols. Currently, there are no widely accepted safety standards or protocols specific to 4DP in construction, largely due to the nascent stage of the technology. This lack of standardization presents a challenge for widespread adoption and could potentially lead to safety and consistency issues. The development of safety standards and protocols is essential for ensuring the reliability and safety of structures built using 4DP technology. These standards would need to address a variety of issues, including the types of materials that can be safely used, the necessary properties of the printed structures, the conditions under which the printing process should take place, and how to handle and dispose of the materials after use [68]. However, the development of such standards is not a straightforward task. It requires comprehensive understanding of the properties of 4D printed materials and structures, as well as thorough testing and validation processes. Moreover, due to the dynamic nature of 4D printed structures, traditional methods of testing and validation may not be suitable, necessitating the development of new methods specific to this technology. In addition, given the global nature of the construction industry, there is a need for international standardization. This raises further challenges, as different countries may have different regulatory requirements and safety standards. Achieving consensus on a global scale can be a complex and time-consuming process. Nevertheless, the development of safety standards and protocols for 4DP in construction is a critical step towards the broader adoption and commercialization of this promising technology.

8. Major hurdles for the implementation of 4D printing in civil engineering

4D printing, while promising, still confronts a host of formidable challenges that hinder its widespread adoption in civil engineering. This section will elaborate on some of the most significant hurdles, namely material constraints, economic feasibility, regulatory considerations, and technical expertise, which are not easily addressable in the short term.

- ***Material Constraints*:** One of the most pressing challenges relates to the materials used in 4DP. While the concept of 4DP—creating objects that can alter their shape or function post-printing in response to certain stimuli—has gained significant traction, the field is in its infancy when it comes to the development of suitable materials. The paucity of materials that can meet the rigorous requirements of civil engineering applications while retaining their 4D capabilities poses a considerable hurdle. Additionally, the environmental implications of the materials, their strength, durability, and the speed at which they can respond to environmental stimuli are all pressing concerns [1,69].
- ***Economic Feasibility*:** The economic feasibility of 4DP in civil engineering is another major challenge. While 3DP has demonstrated its potential to reduce construction costs, the economic benefits of 4DP are yet to be fully substantiated. Current 4DP processes are complex and costly due to the high price of smart materials and the need for sophisticated printing techniques. Therefore, more research and development are required to reduce the costs associated with 4DP to make it economically viable on a large scale in the civil engineering sector [70].
- ***Regulatory Considerations*:** Regulatory issues also present significant challenges for the adoption of 4DP in civil engineering. Given that the technology is relatively new, there are no established regulations or standards specifically designed for 4D printed structures. Regulatory bodies must develop appropriate norms and standards to ensure the safety, quality, and environmental sustainability of 4D printed buildings. In the absence of such standards, the acceptance and deployment of 4DP in construction might be delayed [71,72].
- ***Technical Expertise*:** Lastly, the lack of technical expertise and understanding of 4DP processes is a significant obstacle. The successful deployment of 4DP in civil engineering requires a skilled workforce capable of designing, operating, and maintaining 4DP systems. However, the current scarcity of such skills in the construction industry can hinder the widespread adoption of 4DP [73,74].

  In conclusion, while 4DP harbors immense potential to revolutionize civil engineering, it is not without its challenges. These hurdles—material constraints, economic feasibility, regulatory considerations, and technical expertise—are not insurmountable but will require dedicated research, investment, and policy-making efforts to overcome. Furthermore, the central concept of 4DP rests upon the utilization of 'smart materials'. These materials, remarkable in their capacity to react to environmental stimuli such as changes in temperature, light, moisture, or even magnetic fields, can transform, alter their properties, or self-assemble into complex structures. The potential application of such materials in civil engineering is enormous. From the development of adaptive buildings that can dynamically respond to environmental variations, to the conception of infrastructure capable of self-repair in the event of damage, the possibilities are intriguing [5,66].

However, the practical application of these smart materials in civil engineering opens several challenges. Firstly, these materials need to conform to the demanding performance standards required of traditional construction materials. They need to demonstrate resilience, durability, and strength, capable of withstanding the diverse environmental stressors and loads that civil engineering structures must bear). Additionally, the endurance of these smart materials throughout the 4DP process itself is crucial. They need to be flexible and malleable enough to be extruded or processed by a printer, yet also capable of quickly hardening or solidifying once printed, without compromising their transformative capabilities. This delicate equilibrium between softness required for printing and rigidity necessary after printing is a challenge, as it requires fine control over the material's thermophysical and chemical properties [13,23].

9. The potential of 4D printing in civil engineering

For a clearer and more concise understanding of the differentiating factors between 3D and 4DP technologies, we provide a comparison in Table 2. This comparison encompasses multiple factors, including the strength of the printed structures, the printability of the materials, and the feasibility of each technology in practical applications. It is important to bear in mind that these are general observations, and the specific characteristics may vary depending on the materials and processes employed.

In this section, we explore the broader context of 4DP technology, including the driving forces behind its research, the role of sustainability in its advancement, and the importance of collaboration between academia and industry.

1. Driving Forces Behind 4DP Research; Several factors have contributed to the growing interest in 4DP research:
   - ***Material Science Advancements***: The creation of new materials with adaptive capabilities, such as shape memory polymers, hydrogels, and electroactive polymers, has expanded the possibilities for 4DP applications not only in civil engineering but also in other fields [1].
   - ***Industry 4.0 and Digital Transformation***: The digital transformation across various industries has sparked interest in cutting-edge technologies like 4DP, which can provide intelligent, adaptive, and efficient solutions to complex challenges [77].
   - ***Global Challenges***: Issues such as climate change, urbanization, and resource scarcity have led to an increasing need for sustainable, adaptive, and efficient infrastructure solutions, which 4DP has the potential to address [66].
2. Sustainability and 4DP; Sustainability plays a crucial role in the development and adoption of 4DP technology. With the growing demand for sustainable infrastructure, 4DP can offer numerous advantages, including:
   - ***Decreased Material Usage***: 4DP allows for the creation of adaptive structures that can modify their shape and properties based on environmental conditions, leading to more efficient material usage, and ultimately reducing waste and the environmental impact of construction projects [13].
   - ***Energy Efficiency***: 4D-printed structures' ability to respond to changes in temperature and light conditions can result in more energy-efficient buildings and infrastructure, lowering energy consumption and associated carbon emissions [2].
   - ***Improved Resilience***: Developing disaster-resistant structures using 4DP can contribute to infrastructure resilience, helping mitigate the impacts of climate change and other environmental challenges [78].
3. Academia-Industry Collaboration; The successful implementation of 4DP in civil engineering will require close collaboration between academic institutions and industry partners. This collaboration can take several forms, such as:
   - ***Joint Research Projects***: Collaboration between universities and industry partners on research projects can help advance the development of 4DP materials, design methodologies, and construction processes, ultimately driving the technology's adoption in civil engineering [79].
   - ***Knowledge Transfer***: Knowledge exchange between academia and industry is crucial to ensure that research findings are translated into practical applications and that industry needs are addressed in ongoing research efforts [80].
   - ***Training and Education***: By working together, academic institutions and industry partners can develop training programs and educational initiatives to equip the next generation of civil engineers with the skills and knowledge required to work with 4DP technologies and materials [81].

Table 2
Comparison between 3D and 4DP technologies [8,75,76].

Factors	3DP	4DP
Strength	Depends on the material and printing process	Can be enhanced through smart material properties and stimulus response
Printability	Suitable for a wide range of materials	Limited to smart materials that can respond to stimuli
Feasibility	Mature technology with wide application	Still in early stages, with fewer practical applications
Cost	Varies, generally affordable	Currently more expensive due to specialized materials and processes
Complexity of design	Limited by the mechanical properties of materials	Allows for complex and dynamic designs through stimuli-responsive materials
Time-dependency	Static structures post-production	Structures can change post-production in response to stimuli
Environmental Impact	Depends on the material; some materials recyclable	Potential for less waste due to adaptive and reconfigurable structures

In conclusion, the integration of 4DP technology in civil engineering has the potential to bring about significant advancements in the field. Addressing the challenges associated with this technology and fostering collaborations between various stakeholders will help unlock the full potential of 4DP. As we overcome these hurdles, we can expect to see innovative solutions in the design, construction, and maintenance of our infrastructure that contribute to a more sustainable, efficient, and resilient built environment for the future.

10. Commercialization and current progress of 4D printing in civil engineering

4D printing is an exciting and dynamic field with enormous potential for a wide array of applications, especially in civil engineering [66]. The advent of 4DP technology heralds a new era in construction, where structures can adapt and react to changes in their environment autonomously, thereby enhancing the resilience, longevity, and utility of built environments. Despite being a relatively new technology, several pioneering companies and research institutions are already exploring the potential of commercializing 4DP technology for large-scale, civil engineering applications [13].

One such company is Stratasys, a leader in the field of additive manufacturing, which has been at the forefront of 4DP technology since its inception. Stratasys' 4DP technology uses advanced homopolymers that can be programmed to change shape over time when subjected to water, heat, or light stimuli. Another noteworthy company is Autodesk, whose Project Cyborg platform has been pivotal in the development of digital modeling and simulation tools for 4D printed materials and structures. Despite these technological advancements, there are still several challenges that need to be addressed to further the commercialization of 4DP in civil engineering. Technology's scalability is one of these key challenges. While 4DP has demonstrated great promise at small scales in laboratory settings, scaling up the process to accommodate the size and complexity of civil structures poses significant technical and logistical hurdles. Moreover, the existing 4DP technologies still face issues regarding print speed, material costs, and the reliability of the printed components over time, all of which are critical for commercial applications [2,5,23].

The development of appropriate standards and certifications for 4D-printed civil structures is another crucial aspect of the technology's commercialization process. Given the novel and complex nature of 4D printed materials and structures, creating relevant standards and certifications would help ensure their safety, reliability, and performance. This would also assist in fostering public and industry trust in technology, thereby accelerating its adoption in the construction sector. Moreover, continued interdisciplinary research involving material scientists, civil engineers, architects, and other relevant stakeholders is vital to overcome the existing technological barriers and facilitate the commercialization process. Such collaborative research could focus on developing new smart materials suitable for 4DP, optimizing the 4DP processes for large-scale applications, and exploring novel uses of the technology in civil engineering.

In summary, the journey from laboratory to market for 4DP in civil engineering is still ongoing and filled with challenges. However, the progress made by research institutions and companies such as Stratasys and Autodesk suggests that the commercial reality of 4D-printed civil structures is not too far off. Continued advancements in 4DP technology, coupled with the development of appropriate standards and increased interdisciplinary collaboration, are key to realizing the full potential of this innovative technology in the realm of civil engineering.

11. Design freedom with 4D printing in civil engineering

With rapid technological advancements in additive manufacturing, the era of 4DP is swiftly finding its footing in civil engineering. The fourth dimension, time, opens an array of transformative possibilities that supersede the capabilities of traditional 3DP. This aspect, coupled with the flexibility it offers in terms of design and customization, has established 4DP as an essential frontier of the civil engineering sector. 4D printing, by integrating smart materials and adaptability, offers unprecedented design freedom. This involves the capacity to create complex geometric structures, adaptability to environmental conditions, and the ability to self-assemble and transform over time. This section explores the design freedom that 4DP brings to the civil engineering field and its potential applications and benefits [1].

The geometrical complexity achievable through 4DP is beyond the scope of conventional construction methods. The process allows for intricate designs, including curved, hollow, and interlaced structures, which are difficult to attain with traditional techniques. This increased geometric freedom enables the creation of efficient structural designs that are not only aesthetically pleasing but also offer enhanced performance characteristics. For instance, it allows engineers to optimize the structure's strength-to-weight ratio, potentially leading to significant material and cost savings. Furthermore, 4DP's capability to create adaptive structures opens new horizons for designing buildings that can respond to changes in the environment. This adaptability can range from simple changes in form to more complex responses, such as altering physical properties or functionalities. For example, a 4D printed building facade could be designed to self-shade in response to sunlight, thereby improving the building's energy efficiency. Similarly, in regions prone to earthquakes, buildings could be designed to adjust their structural rigidity in response to seismic activity, enhancing their resilience [3].

The concept of self-assembly is another groundbreaking feature introduced by 4DP. This involves designing objects that can change their shape or assemble themselves from flat components into three-dimensional structures over time under certain conditions. This aspect is especially beneficial in areas that are challenging for humans or machines to reach or work, such as underwater or space structures. It also reduces the need for manual labor, thereby enhancing safety and efficiency. In conclusion, 4DP, with its inherent design freedom, is poised to revolutionize civil engineering. It allows engineers to break free from traditional design constraints, offering unlimited possibilities for creating structures with enhanced performance, efficiency, and resilience. However, it's worth mentioning that these advantages come with their challenges, such as the need for new design and simulation tools, comprehensive understanding of material behaviors, and regulatory frameworks. Therefore, continuous research and development are essential to fully leverage the design freedom offered by 4DP in civil engineering [82,83].

12. Countries and universities that have made significant contributions to the field

In the field of 4DP, several countries and universities have made significant contributions through research, development, and collaboration. Some of the most notable countries and institutions include:

- ***United States:*** Leading American institutions have made substantial contributions to 4DP research, with key players including the Massachusetts Institute of Technology (MIT), Harvard University, University of Colorado, Boulder, Georgia Institute of Technology, and the University of California, Los Angeles (UCLA) [1,5,84,85].
- ***United Kingdom:*** In the UK, prominent universities engaged in 4DP research include the University of Cambridge, University College London (UCL), the University of Bristol, and the University of Nottingham [2,86,87].
- ***Netherlands:*** The Netherlands has made significant contributions to 4DP research through institutions such as Delft University of Technology (TU Delft), Eindhoven University of Technology (TU/e), and the University of Twente [13,58,88].
- ***Germany:*** German institutions actively involved in 4DP research include the Karlsruhe Institute of Technology (KIT) and the Technical University of Munich (TUM) [40,76].
- ***Australia:*** In Australia, RMIT University, the University of Sydney, and the University of Wollongong have made notable contributions to the field of 4DP [89,90].
- ***Singapore:*** Singaporean universities, such as Nanyang Technological University (NTU) and the National University of Singapore (NUS), have been actively engaged in 4DP research [62,91].
- ***China:*** Chinese institutions, including Tsinghua University, Zhejiang University, and Beijing Institute of Technology, have made significant strides in 4DP research and development [92,93].

These institutions have been involved in various aspects of 4DP research, including material development, design methodologies, and applications across different industries. The collaboration between these institutions and others around the world plays a crucial role in advancing the field of 4DP and unlocking its potential for a wide range of applications.

13. Market landscape and trends in 4D printing

As clear from Fig. 7, the global 4DP market is anticipated to witness substantial growth, propelled by factors such as progress in material science, the rising implementation of Industry 4.0 technologies, and the demand for more sustainable, efficient, and adaptive solutions in various sectors, including civil engineering, aerospace, automotive, and healthcare [94].

Although the 4DP market is still relatively small compared to the more established 3DP market, its potential for a wide range of applications has attracted interest from investors, researchers, and industry players. Market growth is expected to be driven by increased research and development and strategic collaborations between universities, research institutions, and industry leaders. Key players in the 4DP market include well-known companies such as Stratasys, 3D Systems, ExOne, Hewlett-Packard, Autodesk, and Organovo. These companies are involved in developing 4DP technologies, materials, and applications, focusing on driving innovation and expanding the market [94].

Market segmentation for 4DP typically encompasses categories such as material type (e.g., shape memory materials, electroactive polymers, hydrogels), end-use industry (e.g., civil engineering, aerospace, automotive, healthcare), and region (e.g., North America, Europe, Asia-Pacific). North America and Europe are expected to be dominant players in the market due to their advanced research infrastructure and strong emphasis on innovation. As the technology matures and gains wider adoption, the 4DP market is likely to experience significant growth, driven by increasing demand for smart, adaptive, and sustainable solutions across various industries. However, challenges such as material development, scalability, and regulatory issues must be addressed to fully realize the potential of 4DP technology in the global market [94].

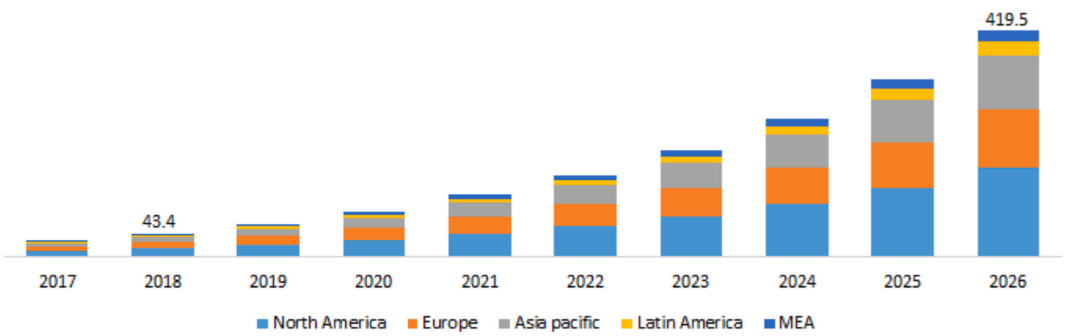

Fig. 7. Global 4DP market by region, 2017–2026 (USD Million) [94].

14. Prospects and potential impact of 4D printing

As 4D printing technology continues to advance, it is poised to have a transformative impact on various industries and applications, ranging from civil engineering and aerospace to healthcare and consumer goods. The future of 4DP will likely be shaped by ongoing research and development, as well as the increasing adoption of Industry 4.0 technologies and the demand for more sustainable, efficient, and adaptive solutions [94].

- ***Expansion of Applications:*** The potential applications of 4DP are expected to grow and diversify, leading to the development of innovative products and solutions. For instance, in civil engineering, 4D-printed structures may become more prevalent in the construction of energy-efficient buildings and disaster-resistant infrastructure. In healthcare, 4DP could be employed to create customized medical devices and implants that adapt to a patient's needs [1].
- ***Advancements in Material Science:*** Further advancements in material science will be crucial to unlocking the full potential of 4DP. The development of new materials with enhanced adaptive capabilities, such as improved shape memory polymers, hydrogels, and electroactive polymers, will pave the way for more sophisticated and versatile 4DP applications [3].
- ***Addressing Challenges and Limitations:*** To fully capitalize on the potential of 4DP, several challenges and limitations need to be addressed. These include the scalability of 4DP processes, the development of efficient design and simulation tools, and the establishment of regulatory frameworks to ensure the safety and reliability of 4D-printed products [94].

In conclusion, the future of 4DP looks promising, with the potential to revolutionize a wide range of industries and applications. By addressing the associated challenges and capitalizing on the opportunities it presents, 4DP could play a significant role in shaping a more sustainable, efficient, and adaptive future.

15. Conclusion

As we stand on the brink of a technological revolution in civil engineering and construction technology, the integration of 4DP represents a significant step forward. Throughout this paper, we have explored the mechanism of 4DP, the materials used, and its current applications and future possibilities in civil engineering. The 4DP technology, characterized by its unique time-responsive transformation feature, presents numerous opportunities for the creation of adaptive and resilient structures. In this manuscript, the significant of findings and implications were:

- ***The Role of Smart Materials:*** As we have outlined, smart materials play an instrumental role in 4DP. Materials such as shape memory alloys, hydrogels, and bio-based substrates offer the potential for environmental responsiveness, giving rise to structures capable of adapting to changing environmental conditions.
- ***Design Freedom:*** The adoption of 4DP in civil engineering grants remarkable design freedom. With its ability to fabricate complex geometric structures that were previously challenging or impossible, it allows for a new era of architectural creativity and efficiency.
- ***Resilience and Sustainability:*** With the capacity for transformation and adaptation, 4D-printed structures offer significant potential for increased resilience, particularly in the face of environmental stressors like seismic activity. In addition, the potential use of renewable, bio-based materials in 4DP could lead to more sustainable construction practices, though this is a field that requires more exploration and innovation.
- ***Technological Limitations and Future Development:*** Despite the remarkable potential of 4DP, it's crucial to acknowledge its current limitations. Challenges exist in terms of material performance, printing technology, scalability, and cost. However, ongoing advancements suggest promising future developments in these areas, possibly opening more opportunities for large-scale applications of 4DP in civil engineering.
- In summary, the integration of 4DP into civil engineering heralds an exciting new era for the field, filled with innovative solutions and potential. It brings forth unprecedented design freedom, the ability to create adaptable, resilient structures, and possibilities for greater sustainability. While challenges still exist, ongoing advancements in materials science and printing technologies continue to push the boundaries of what is achievable. The review has outlined how the adoption of 4DP technology could revolutionize civil engineering, but it's clear that the journey is only just beginning. It is hoped that this overview will inspire further research and innovation in this exciting intersection of 4DP and civil engineering, leading to a future where the full potential of this groundbreaking technology can be realized.
- In the face of an ever-changing global landscape, the need for adaptable, resilient, and sustainable infrastructure has never been more important. As 4DP technology continues to evolve, it offers the promise of a future where our built environment can better respond to and shape the world around us. Thus, this review sets the stage for an exciting journey of discovery and innovation in the world of 4DP, shedding light on the potential applications, challenges, and future directions of this emergent technology in the field of civil engineering. Its potential to transform how we design, construct, and interact with our built environment is a prospect that holds immense promise and invites further exploration.

CRediT authorship contribution statement

Ali Akbar Firoozi: Formal analysis, Methodology, Project administration, Resources, Supervision, Validation, Visualization,

Writing – original draft, Writing – review & editing. **Ali Asghar Firoozi:** Data curation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] S. Tibbits, 4D printing: multi-material shape change, Architect. Des 84 (1) (2014) 116–121, https://doi.org/10.1002/ad.1710.
[2] F. Momeni, X. Liu, J. Ni, A review of 4D printing, Mater. Des. 122 (2017) 42–79, https://doi.org/10.1016/j.matdes.2017.02.068.
[3] Q. Ge, H.J. Qi, M.L. Dunn, Active materials by four-dimension printing, Appl. Phys. Lett. 103 (13) (2013), https://doi.org/10.1063/1.4819837.
[4] C.W. Isaac, F. Duddeck, Current trends in additively manufactured (3D printed) energy absorbing structures for crashworthiness application–a review, Virtual Phys. Prototyp. 17 (4) (2022) 1058–1101, https://doi.org/10.1080/17452759.2022.2074698.
[5] U.K. Vates, S. Mishra, N.J. Kanu, Biomimetic 4D printed materials: a state-of-the-art review on concepts, opportunities, and challenges, Mater. Today: Proc. 47 (2021) 3313–3319, https://doi.org/10.1016/j.matpr.2021.07.148.
[6] Z. Zhang, K.G. Demir, G.X. Gu, Developments in 4D-printing: a review on current smart materials, technologies, and applications, Int. J. Soc. Netw. Min. 10 (3) (2019) 205–224, https://doi.org/10.1080/19475411.2019.1591541.
[7] C. Maraveas, I.S. Bayer, T. Bartzanas, 4D printing: perspectives for the production of sustainable plastics for agriculture, Biotechnol. Adv. 54 (2022), 107785, https://doi.org/10.1016/j.biotechadv.2021.107785.
[8] K.L. Ameta, V.S. Solanki, S. Haque, V. Singh, A.P. Devi, R.S. Chundawat, Critical appraisal and systematic review of 3D & 4D printing in sustainable and environment-friendly smart manufacturing technologies, Sustainable Materials and Technologies (2022), e00481, https://doi.org/10.1016/j.susmat.2022.e00481.
[9] S. Ram Kishore, A.P. Sridharan, U. Chadha, D. Narayanan, M. Mishra, S.K. Selvaraj, A.E. Patterson, Natural fiber biocomposites via 4D printing technologies: a review of possibilities for agricultural bio-mulching and related sustainable applications, Progress in Additive Manufacturing (2023) 1–31, https://doi.org/10.1007/s40964-023-00433-8.
[10] A. Subash, B. Kandasubramanian, 4D printing of shape memory polymers, Eur. Polym. J. 134 (2020), 109771, https://doi.org/10.1016/j.eurpolymj.2020.109771.
[11] J.L. Alves, L. Santana, B. Rangel, 4D printing and construction: reality, future, or science fiction?, in: 3D Printing for Construction with Alternative Materials Springer International Publishing, Cham, 2023, pp. 155–175, https://doi.org/10.1007/978-3-031-09319-7_7.
[12] C. Debrah, A.P. Chan, A. Darko, Artificial intelligence in green building, Autom. ConStruct. 137 (2022), 104192, https://doi.org/10.1016/j.autcon.2022.104192.
[13] C. Yuan, F. Wang, Q. Ge, Multimaterial direct 4D printing of high stiffness structures with large bending curvature, Extreme Mechanics Letters 42 (2021), 101122, https://doi.org/10.1016/j.eml.2020.101122.
[14] E. Pei, J. Shen, J. Watling, Direct 3D printing of polymers onto textiles: experimental studies and applications, Rapid Prototyp. J. 21 (5) (2015) 556–571, https://doi.org/10.1108/RPJ-09-2014-0126.
[15] M. Quanjin, M.R.M. Rejab, M.S. Idris, N.M. Kumar, M.H. Abdullah, G.R. Reddy, Recent 3D and 4D intelligent printing technologies: a comparative review and future perspective, Proc. Comput. Sci. 167 (2020) 1210–1219, https://doi.org/10.1016/j.procs.2020.03.434.
[16] F.E. Azhar, A 4D Printing Communication Framework for Designers and Engineers (Doctoral Dissertation, Brunel University London, 2022.
[17] M. Mehrpouya, A. Dehghanghadikolaei, B. Fotovvati, A. Vosooghnia, S.S. Emamian, A. Gisario, The potential of additive manufacturing in the smart factory industrial 4.0: a review, Appl. Sci. 9 (18) (2019) 3865, https://doi.org/10.3390/app9183865.
[18] H. Yi, Y. Kim, Prototyping of 4D-printed self-shaping building skin in architecture: design, fabrication, and investigation of a two-way shape memory composite (TWSMC) façade panel, J. Build. Eng. 43 (2021), 103076, https://doi.org/10.1016/j.jobe.2021.103076.
[19] X. Liu, M. Wei, Q. Wang, Y. Tian, J. Han, H. Gu, Z. Gu, Capillary-force-driven self-assembly of 4d-printed microstructures, Adv. Mater. 33 (22) (2021), 2100332, https://doi.org/10.1002/adma.202100332.
[20] C.K. Khoo, F. Salim, J. Burry, Designing architectural morphing skins with elastic modular systems, Int. J. Architect. Comput. 9 (4) (2011) 397–419, https://doi.org/10.1260/1478-0771.9.4.397.
[21] M.I. Farid, W. Wu, L. Guiwei, Z. Yu, Research on imminent enlargements of smart materials and structures towards novel 4D printing (4DP: SMs-SSs), Int. J. Adv. Des. Manuf. Technol. 126 (7–8) (2023) 2803–2823, https://doi.org/10.1007/s00170-023-11180-z.
[22] M.Y. Khalid, Z.U. Arif, W. Ahmed, 4D printing: technological and manufacturing renaissance, Macromol. Mater. Eng. 307 (8) (2022), 2200003, https://doi.org/10.1002/mame.202200003.
[23] L. Joharji, R.B. Mishra, F. Alam, S. Tytov, F. Al-Modaf, N. El-Atab, 4D printing: a detailed review of materials, techniques, and applications, Microelectron. Eng. (2022), 111874, https://doi.org/10.1016/j.mee.2022.111874.
[24] N. Makul, Advanced smart concrete-A review of current progress, benefits and challenges, J. Clean. Prod. 274 (2020), 122899, https://doi.org/10.1016/j.jclepro.2020.122899.
[25] H.J. Chen, C.F. Peng, C.W. Tang, Y.T. Chen, Self-healing concrete by biological substrate, Materials 12 (24) (2019) 4099, https://doi.org/10.3390/ma12244099.
[26] L. Santo, F. Quadrini, D. Bellisario, L. Iorio, Applications of shape-memory polymers, and their blends and composites, Shape Memory Polymers, Blends and Composites: Advances and Applications (2020) 311–329, https://doi.org/10.1007/978-981-13-8574-2_13.
[27] B. Jian, F. Demoly, Y. Zhang, H.J. Qi, J.C. André, S. Gomes, Origami-based design for 4D printing of 3D support-free hollow structures, Eng. Times 12 (2022) 70–82, https://doi.org/10.1016/j.eng.2021.06.028.
[28] H. Vahabi, F. Laoutid, M. Mehrpouya, M.R. Saeb, P. Dubois, Flame retardant polymer materials: an update and the future for 3D printing developments, Mater. Sci. Eng. R Rep. 144 (2021), 100604, https://doi.org/10.1016/j.mser.2020.100604.

[29] I. Shah, L. Jing, Z.M. Fei, Y.S. Yuan, M.U. Farooq, N. Kanjana, A review on chemical modification by using sodium hydroxide (NaOH) to investigate the mechanical properties of sisal, coir and hemp fiber reinforced concrete composites, J. Nat. Fibers 19 (13) (2022) 5133–5151, https://doi.org/10.1080/15440478.2021.1875359.

[30] Y. Xia, Y. He, F. Zhang, Y. Liu, J. Leng, A review of shape memory polymers and composites: mechanisms, materials, and applications, Adv. Mater. 33 (6) (2021), 2000713, https://doi.org/10.1002/adma.202000713.

[31] A. Megdich, M. Habibi, L. Laperriere, A review on 4D printing: material structures, stimuli and additive manufacturing techniques, Mater. Lett. (2023), 133977, https://doi.org/10.1016/j.matlet.2023.133977.

[32] O.A. Alo, D. Mauchline, I.O. Otunniyi, 3D-Printed functional polymers and nanocomposites: defects characterization and product quality improvement, Adv. Eng. Mater. 24 (5) (2022), 2101219, https://doi.org/10.1002/adem.202101219.

[33] D. Athinarayanarao, R. Prod'hon, D. Chamoret, H.J. Qi, M. Bodaghi, J.C. André, F. Demoly, Computational design for 4D printing of topology optimized multi-material active composites, npj Comput. Mater. 9 (1) (2023) 1, https://doi.org/10.1038/s41524-022-00962-w.

[34] M. Champeau, D.A. Heinze, T.N. Viana, E.R. de Souza, A.C. Chinellato, S. Titotto, 4D printing of hydrogels: a review, Adv. Funct. Mater. 30 (31) (2020), 1910606, https://doi.org/10.1002/adfm.201910606.

[35] A. Ahmed, S. Arya, V. Gupta, H. Furukawa, A. Khosla, 4D printing: fundamentals, materials, applications and challenges, Polymer 228 (2021), 123926, https://doi.org/10.1016/j.polymer.2021.123926.

[36] S.B. Kumar, J. Jeevamalar, P. Ramu, G. Suresh, K. Senthilnathan, Evaluation in 4D printing–a review, Mater. Today: Proc. 45 (2021) 1433–1437, https://doi.org/10.1016/j.matpr.2020.07.335.

[37] F. Kabirian, P. Mela, R. Heying, 4D printing applications in the development of smart cardiovascular implants, Front. Bioeng. Biotechnol. 10 (2022), 873453, https://doi.org/10.3389/fbioe.2022.873453.

[38] A. Mahmood, T. Akram, H. Chen, S. Chen, On the evolution of additive manufacturing (3D/4D printing) technologies: materials, applications, and challenges, Polymers 14 (21) (2022) 4698, https://doi.org/10.3390/polym14214698.

[39] B. Subeshan, Y. Baddam, E. Asmatulu, Current progress of 4D-printing technology, Progress in Additive Manufacturing 6 (2021) 495–516, https://doi.org/10.1007/s40964-021-00182-6.

[40] S. Miao, W. Zhu, N.J. Castro, J. Leng, L.G. Zhang, Four-dimensional printing hierarchy scaffolds with highly biocompatible smart polymers for tissue engineering applications, Tissue Eng. C Methods 22 (10) (2016) 952–963, https://doi.org/10.1089/ten.tec.2015.0542.

[41] Y. Wang, H. Cui, T. Esworthy, D. Mei, Y. Wang, L.G. Zhang, Emerging 4D printing strategies for next-generation tissue regeneration and medical devices, Adv. Mater. 34 (20) (2022), 2109198, https://doi.org/10.1002/adma.202109198.

[42] W. Zhao, F. Zhang, J. Leng, Y. Liu, Personalized 4D printing of bioinspired tracheal scaffold concept based on magnetic stimulated shape memory composites, Compos. Sci. Technol. 184 (2019), 107866, https://doi.org/10.1016/j.compscitech.2019.107866.

[43] M. Regehly, Y. Garmshausen, M. Reuter, N.F. König, E. Israel, D.P. Kelly, S. Hecht, Xolography for linear volumetric 3D printing, Nature 588 (7839) (2020) 620–624, https://doi.org/10.1038/s41586-020-3029-7.

[44] Q. Ge, Z. Li, Z. Wang, K. Kowsari, W. Zhang, X. He, N.X. Fang, Projection micro stereolithography based 3D printing and its applications, Int. J. Extrem. Manuf. 2 (2) (2020), 022004, https://doi.org/10.1088/2631-7990/ab8d9a.

[45] A. Kafle, E. Luis, R. Silwal, H.M. Pan, P.L. Shrestha, A.K. Bastola, 3D/4D Printing of polymers: Fused deposition modelling (FDM), selective laser sintering (SLS), and stereolithography (SLA), Polymers 13 (18) (2021) 3101, https://doi.org/10.3390/polym13183101.

[46] C. Lin, L. Liu, Y. Liu, J. Leng, 4D printing of shape memory polybutylene succinate/polylactic acid (PBS/PLA) and its potential applications, Compos. Struct. 279 (2022), 114729, https://doi.org/10.1016/j.compstruct.2021.114729.

[47] A.A. Konta, M. García-Piña, D.R. Serrano, Personalised 3D printed medicines: which techniques and polymers are more successful? Bioengineering 4 (4) (2017) 79, https://doi.org/10.3390/bioengineering4040079.

[48] H. Kadry, S. Wadnap, C. Xu, F. Ahsan, Digital light processing (DLP) 3D-printing technology and photoreactive polymers in fabrication of modified-release tablets, Eur. J. Pharmaceut. Sci. 135 (2019) 60–67, https://doi.org/10.1016/j.ejps.2019.05.008.

[49] X. Yu, T. Zhang, Y. Li, 3D printing and bioprinting nerve conduits for neural tissue engineering, Polymers 12 (8) (2020) 1637, https://doi.org/10.3390/polym12081637.

[50] C.A. Spiegel, M. Hackner, V.P. Bothe, J.P. Spatz, E. Blasco, 4D printing of shape memory polymers: from macro to micro, Adv. Funct. Mater. 32 (51) (2022), 2110580, https://doi.org/10.1002/adfm.202110580.

[51] M.R. Manshor, Y.A. Alli, H. Anuar, O. Ejeromedoghene, E.O. Omotola, J. Suhr, 4D printing: historical evolution, computational insights and emerging applications, Mater. Sci. Eng., B 295 (2023), 116567, https://doi.org/10.1016/j.mseb.2023.116567.

[52] S. Vatanparast, A. Boschetto, L. Bottini, P. Gaudenzi, New trends in 4D printing: a critical review, Appl. Sci. 13 (13) (2023) 7744, https://doi.org/10.3390/app13137744.

[53] C. Cui, L. An, Z. Zhang, M. Ji, K. Chen, Y. Yang, Y. Zhang, Reconfigurable 4D printing of reprocessable and mechanically strong polythiourethane covalent adaptable networks, Adv. Funct. Mater. 32 (29) (2022), 2203720, https://doi.org/10.1002/adfm.202203720.

[54] M.C. Biswas, S. Chakraborty, A. Bhattacharjee, Z. Mohammed, 4D printing of shape memory materials for textiles: mechanism, mathematical modeling, and challenges, Adv. Funct. Mater. 31 (19) (2021), 2100257, https://doi.org/10.1002/adfm.202100257.

[55] A.K. Akhnoukh, Advantages of contour crafting in construction applications, Recent Pat. Eng. 15 (3) (2021) 294–300, https://doi.org/10.2174/1872212114666200218111631.

[56] A.I. Salimon, F.S. Senatov, V. Kalyaev, A.M. Korsunsky, Shape memory polymer blends and composites for 3D and 4D printing applications, in: 3D and 4D Printing of Polymer Nanocomposite Materials, Elsevier, 2020, pp. 161–189, https://doi.org/10.1016/B978-0-12-816805-9.00006-5.

[57] S. Miao, N. Castro, M. Nowicki, L. Xia, H. Cui, X. Zhou, L.G. Zhang, 4D printing of polymeric materials for tissue and organ regeneration, Mater. Today 20 (10) (2017) 577–591, https://doi.org/10.1016/j.mattod.2017.06.005.

[58] M. Nachimuthu, R. Pk, Inkjet four-dimensional printing of shape memory polymers: a review, Rapid Prototyp. J. 29 (3) (2023) 437–446, https://doi.org/10.1108/RPJ-08-2021-0198.

[59] F. Craveiro, J.P. Duarte, H. Bártolo, P. Bártolo, Moving forward to 3D/4D printed building facades, in: Progress in Digital and Physical Manufacturing: Proceedings of ProDPM'19, Springer International Publishing, 2020, pp. 277–282, https://doi.org/10.1007/978-3-030-29041-2_35.

[60] A. Haleem, M. Javaid, R.P. Singh, R. Suman, Significant roles of 4D printing using smart materials in the field of manufacturing, Advanced Industrial and Engineering Polymer Research 4 (4) (2021) 301–311, https://doi.org/10.1016/j.aiepr.2021.05.001.

[61] F. Demoly, M.L. Dunn, K.L. Wood, H.J. Qi, J.C. Andre, The status, barriers, challenges, and future in design for 4D printing, Mater. Des. 212 (2021), 110193, https://doi.org/10.1016/j.matdes.2021.110193.

[62] S. Joshi, K. Rawat, C. Karunakaran, V. Rajamohan, A.T. Mathew, K. Koziol, A.S.S. Balan, 4D printing of materials for the future: opportunities and challenges, Appl. Mater. Today 18 (2020), 100490, https://doi.org/10.1016/j.apmt.2019.100490.

[63] Y.S. Alshebly, K.B. Mustapha, A. Zolfagharian, M. Bodaghi, M.S. Mohamed Ali, H.A. Almurib, M. Nafea, Bioinspired pattern-driven single-material 4D printing for self-morphing actuators, Sustainability 14 (16) (2022), 10141, https://doi.org/10.3390/su141610141.

[64] S. Pessoa, A.S. Guimarães, S.S. Lucas, N. Simões, 3D printing in the construction industry-A systematic review of the thermal performance in buildings, Renew. Sustain. Energy Rev. 141 (2021), 110794, https://doi.org/10.1016/j.rser.2021.110794.

[65] X. Qi, G. Chen, Y. Li, X. Cheng, C. Li, Applying neural-network-based machine learning to additive manufacturing: current applications, challenges, and future perspectives, Eng. Times 5 (4) (2019) 721–729, https://doi.org/10.1016/j.eng.2019.04.012.

[66] Z.X. Khoo, J.E.M. Teoh, Y. Liu, C.K. Chua, S. Yang, J. An, W.Y. Yeong, 3D printing of smart materials: a review on recent progresses in 4D printing, Virtual Phys. Prototyp. 10 (3) (2015) 103–122, https://doi.org/10.1080/17452759.2015.1097054.

[67] B. Singh, R. Kumar, J.S. Chohan, Polymer matrix composites in 3D printing: a state of art review, Mater. Today: Proc. 33 (2020) 1562–1567, https://doi.org/10.1016/j.matpr.2020.04.335.

[68] E. Pei, G.H. Loh, S. Nam, Concepts and terminologies in 4D printing, Appl. Sci. 10 (13) (2020) 4443, https://doi.org/10.3390/app10134443.
[69] Y. Zhou, Y. Yang, A. Jian, T. Zhou, G. Tao, L. Ren, Z. Zhang, Co-extrusion 4D printing of shape memory polymers with continuous metallic fibers for selective deformation, Compos. Sci. Technol. 227 (2022), 109603, https://doi.org/10.1016/j.compscitech.2022.109603.
[70] R. Singh, R.M. Holmukhe, A. Gandhar, K. Kumawat, 5D Printing: a future beyond the scope of 4D printing with application of smart materials, J. Inf. Optim. Sci. 43 (1) (2022) 155–167, https://doi.org/10.1080/02522667.2022.2039462.
[71] X. Zhou, L. Ren, Z. Song, G. Li, J. Zhang, B. Li, Q. Liu, Advances in 3D/4D printing of mechanical metamaterials: from manufacturing to applications, Compos. B Eng. 110585 (2023), https://doi.org/10.1016/j.compositesb.2023.110585.
[72] Y. Tahouni, T. Cheng, D. Wood, R. Sachse, R. Thierer, M. Bischoff, A. Menges, Self-shaping curved folding: a 4D-printing method for fabrication of self-folding curved crease structures, in: Proceedings of the 5th Annual ACM Symposium on Computational Fabrication, 2020, November, pp. 1–11, https://doi.org/10.1145/3424630.3425416.
[73] D. Ravichandran, W. Xu, S. Jambhulkar, Y. Zhu, M. Kakarla, M. Bawareth, K. Song, Intrinsic field-induced nanoparticle assembly in three-dimensional (3D) printing polymeric composites, ACS Appl. Mater. Interfaces 13 (44) (2021) 52274–52294, https://doi.org/10.1021/acsami.1c12763.
[74] S. Chakraborty, M.C. Biswas, 3D printing technology of polymer-fiber composites in textile and fashion industry: a potential roadmap of concept to consumer, Compos. Struct. 248 (2020), 112562, https://doi.org/10.1016/j.compstruct.2020.112562.
[75] M.Y. Khalid, Z.U. Arif, R. Noroozi, A. Zolfagharian, M. Bodaghi, 4D printing of shape memory polymer composites: a review on fabrication techniques, applications, and future perspectives, J. Manuf. Process. 81 (2022) 759–797, https://doi.org/10.1016/j.jmapro.2022.07.035.
[76] M.Y. Khalid, Z.U. Arif, W. Ahmed, R. Umer, A. Zolfagharian, M. Bodaghi, 4D printing: technological developments in robotics applications, Sensor Actuator Phys. 343 (2022), 113670, https://doi.org/10.1016/j.sna.2022.113670.
[77] E. Mahmoodi, M. Fathi, M. Ghobakhloo, The impact of Industry 4.0 on bottleneck analysis in production and manufacturing: current trends and future perspectives, Comput. Ind. Eng. 174 (2022), 108801, https://doi.org/10.1016/j.cie.2022.108801.
[78] F. Hamidi, F. Aslani, Additive manufacturing of cementitious composites: materials, methods, potentials, and challenges, Construct. Build. Mater. 218 (2019) 582–609, https://doi.org/10.1016/j.conbuildmat.2019.05.140.
[79] J. Siivonen, S. Pöysäri, A.M. Hakamäki, M. Lanz, K. Salminen, M. Ijas, H. Nieminen, Reconfigurable pilot lines enabling industry digitalization: an approach for transforming industry and academia needs to requirements specifications, Procedia CIRP 107 (2022) 1226–1231, https://doi.org/10.1016/j.procir.2022.05.136.
[80] M. Norouzi, M. Chàfer, L.F. Cabeza, L. Jiménez, D. Boer, Circular economy in the building and construction sector: a scientific evolution analysis, J. Build. Eng. 44 (2021), 102704, https://doi.org/10.1016/j.jobe.2021.102704.
[81] S. Ling, P.I. Itoua, D. Sun, D. Jelagin, Damage characterization of pouring semi-flexible pavement material under triaxial compressive load based on X-ray computed tomography, Construct. Build. Mater. 348 (2022), 128653, https://doi.org/10.1016/j.conbuildmat.2022.128653.
[82] S.S. Imam, A. Hussain, M.A. Altamimi, S. Alshehri, Four-dimensional printing for hydrogel: theoretical concept, 4d materials, shape-morphing way, and future perspectives, Polymers 13 (21) (2021) 3858, https://doi.org/10.3390/polym13213858.
[83] Z. Song, L. Ren, C. Zhao, H. Liu, Z. Yu, Q. Liu, L. Ren, Biomimetic nonuniform, dual-stimuli self-morphing enabled by gradient four-dimensional printing, ACS Appl. Mater. Interfaces 12 (5) (2020) 6351–6361, https://doi.org/10.1021/acsami.9b17577.
[84] Y.C. Huang, Q.P. Cheng, U.S. Jeng, S.H. Hsu, A biomimetic bilayer hydrogel actuator based on thermoresponsive gelatin methacryloyl–poly (N-isopropylacrylamide) hydrogel with three-dimensional printability, ACS Appl. Mater. Interfaces 15 (4) (2023) 5798–5810, https://doi.org/10.1021/acsami.2c18961.
[85] H.A. Alshahrani, Review of 4D printing materials and reinforced composites: behaviors, applications and challenges, J. Sci.: Advanced Materials and Devices 6 (2) (2021) 167–185, https://doi.org/10.1016/j.jsamd.2021.03.006.
[86] M. Bodaghi, R. Noroozi, A. Zolfagharian, M. Fotouhi, S. Norouzi, 4D printing self-morphing structures, Materials 12 (8) (2019) 1353, https://doi.org/10.3390/ma12081353.
[87] S.E. Bakarich, R. Gorkin III, M.I.H. Panhuis, G.M. Spinks, 4D printing with mechanically robust, thermally actuating hydrogels, Macromol. Rapid Commun. 36 (12) (2015) 1211–1217, https://doi.org/10.1002/marc.201500079.
[88] Z. Guan, L. Wang, J. Bae, Advances in 4D printing of liquid crystalline elastomers: materials, techniques, and applications, Mater. Horiz. 9 (7) (2022) 1825–1849, https://doi.org/10.1039/D2MH00232A.
[89] H. Deng, C. Zhang, K. Sattari, Y. Ling, J.W. Su, Z. Yan, J. Lin, 4D printing elastic composites for strain-tailored multistable shape morphing, ACS Appl. Mater. Interfaces 13 (11) (2020) 12719–12725, https://doi.org/10.1021/acsami.0c17618.
[90] M.N.I. Shiblee, K. Ahmed, M. Kawakami, H. Furukawa, 4D printing of shape-memory hydrogels for soft-robotic functions, Advanced Materials Technologies 4 (8) (2019), 1900071, https://doi.org/10.1002/admt.201900071.
[91] Y. Liu, B. Shaw, M.D. Dickey, J. Genzer, Sequential self-folding of polymer sheets, Sci. Adv. 3 (3) (2017), e1602417, https://doi.org/10.1126/sciadv.1602417.
[92] X. Wang, Y. He, Y. Liu, J. Leng, Advances in shape memory polymers: remote actuation, multi-stimuli control, 4D printing and prospective applications, Mater. Sci. Eng. R Rep. 151 (2022), 100702, https://doi.org/10.1016/j.mser.2022.100702.
[93] H. Du, J. Wang, N. Xu, Y. Yu, S. Liu, Transparent, self-healable, shape memory poly (vinyl alcohol)/ionic liquid difunctional hydrogels assembled spontaneously from polymer solution, J. Mol. Liq. 366 (2022), 120226, https://doi.org/10.1016/j.molliq.2022.120226.
[94] F.K. Aldawood, A comprehensive review of 4D printing: state of the arts, opportunities, and challenges, Actuators 12 (No. 3) (2023) 101, https://doi.org/10.3390/act12030101. MDPI.