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ADDITIVE MANUFACTURING IN CONSTRUCTION: STATE OF THE ART AND EMERGING TRENDS IN CIVIL ENGINEERING

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SUMMARY*: For decades, there has been an increasing interest in the development of Additive Manufacturing (AM) in both the construction industry and civil engineering. The rapid evolution of this field requires a review to maintain a global vision. This has led to the emergence of large robotic arm and gantry systems capable of printing building components using various materials such as concrete, including supplementary cementitious materials or natural fibres. Other less recent technologies, such as Fused Deposition Modelling and Laminated Object Manufacturing contribute to the production of components for construction. AM offers several advantages including automated production processes and design flexibility for complex geometry. This article provides an overview of the current state of AM in construction, including an examination of engineering and AM processes, concretes and reinforced materials, advanced materials, and the development of new applications. Additionally, the article discusses recent standards for 3D Concrete Printing. It is aimed at those seeking a comprehensive understanding of AM and its applications in construction 5.0.*

KEYWORDS*: additive manufacturing, construction, building, 3D printing, concrete.*

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1. ADDITIVE MANUFACTURING

Additive manufacturing (AM), also known as 3D printing, has emerged as a disruptive technology in construction and civil engineering, offering the potential to transform the building and construction activities. Large-scale robotic arms and gantry systems have been developed to print building components using various materials, enabling the creation of complex structures with precision and efficiency. Established AM technologies like Fused Deposition Modelling (FDM) and Laminated Object Manufacturing (LOM) also contribute to several materials and manufacturing processes. AM automation streamlines production processes, reduces costs, and enables the achievement of highly customized designs that are challenging with traditional methods. The technology's design flexibility allows for the creation of structures with complex geometries and optimized performance characteristics through improved materials. Additionally, AM integrates advanced numerical simulations into the design and manufacturing process, enabling engineers to predict component behaviour under various conditions, leading to improved performance and durability.

To achieve the optimal functional and mechanical properties of 3D Concrete Printing (3DCP), the material must exhibit specific rheological characteristics essential for effective extrusion. First, pumpability, defined as the material's ability to be transported to the print head via a pumping system within a predetermined time frame. Second, extrudability, which pertains to the material's capability to be extruded uniformly and continuously through the print head. Lastly, buildability, which refers to the material's capacity to maintain the structural integrity of layers post-extrusion and to support the weight of successive layers deposited during the printing process. These properties are critical to ensuring the quality and stability of structures fabricated using 3DCP technology.

This article provides a comprehensive overview of the current state of AM in construction, highlighting various processes, materials, and emerging applications. By exploring the latest advancements and trends in AM, you will gain insights into its potential to shape the future of construction and civil engineering.

2. TECHNOLOGIES, ENGINEERING, AND MANUFACTURING PROCESS

2.1 From Computer Aided Engineering to AM

The additive principle is based on layer-by-layer manufacturing, which begins with creating a three-dimensional object using computer-aided design (CAD). This object is then converted into an STL (Standard Tessellation Language) format, which slices the object into layers using specific software. An STL file is composed of numerous triangular surfaces, and the number increases depending on the size or precision of the 3D model. The STL 3D model is sliced by post-processing software to generate deposition trajectories in the form of G-code. G-code remains the dominant manual programming language for CNC machine tools (Xu 2009). It is also the primary form of control commands output by many CAD/CAM (or CAM) systems. Among the major advances that this process offers to product development are time and cost reduction, minimized human interaction, and consequently, shorter product development cycles (Ashley 1991).

An alternative method adopting the Curved Layered Fused Deposition Modelling (CLFDM) principle, which generates a curved-layered printing path, has been developed using a single scripting environment called Grasshopper – a plugin for Rhinoceros® for 3DCP (Lim et al. 2016). Grasshopper (Associates, s. d.), a plugin for Rhinoceros is a flexible parametric design tool that allows the creation of new algorithms or the modification of existing ones within a graphical scripting environment. It provides freedom and flexibility to designers, including those without programming or scripting experience. This advancement holds promise for enhancing large-scale Additive Manufacturing (AM) techniques, notably by reducing the staircase effect on curved surfaces—a prominent drawback of conventional flat-layered paths. Grasshopper, a plugin for Rhinoceros, was effectively employed to harness the potential of generating curved-layered printing paths and converting them to G-code within a unified scripting environment (Lim et al. 2016). In the context of generative design, Grasshopper is used to create algorithms that automatically generate shapes, structures, or configurations, relying on parameters and rules defined through AM parameters.

Some studies lack of detailed experimental evaluations to validate the actual performance of curved-layered printing trajectories in large-scale applications, as well as the absence of a comprehensive comparative analysis between the Curved Layered Fused Deposition Modelling (CLFDM) method and traditional approaches in terms of precision, cost, and mechanical constraints of the produced components.

2.2 Digital twin in 3DCP

Digital Twin (DT) technology, involving the creation of a virtual replica of a physical object, process, or system, has become a transformative approach in the field of 3D printing. This digital counterpart is utilized for simulation, analysis, and control, enabling real-time monitoring and optimization (Cimino et al., 2019). The core attributes of DTs, including synchronization, bidirectional information flow, learning and adaptability, monitoring capabilities, predictive and prescriptive functions, and optimization, make them particularly valuable in this domain (Nwogu et al., 2022).

Efforts in the literature to develop conceptual models for DT highlight their foundational importance. For instance, Damjanovic-Behrendt and Behrendt (2019) identify three main technology building blocks essential for the realization of a DT: components for managing data, models, and services. Additionally, Tao et al. (2019) propose a five-dimension architecture that provides a comprehensive framework for developing DT solutions, encompassing Physical Entity, Virtual Entity, Services, DT Data, and Connection.

DTs are effectively utilized across various lifecycle phases in 3D printing: planning and design, construction, and operation and maintenance (Wang et al., 2023). During the planning and design phase, DTs optimize design and reduce trial-and-error costs through information integration and real-time simulations. In the construction phase, real-time bidirectional information interaction enhances scheduling accuracy and control of printing systems, minimizing disruptions. In the maintenance phase, DTs monitor structural status and share information for long-term analysis and maintenance (Wang et al., 2023).

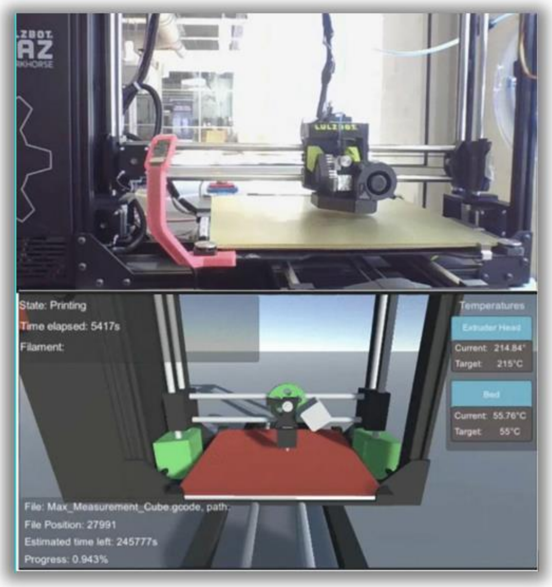
To ensure DT functionality, precise representations of hardware, environment, software inputs, and sensor data are essential (Kantaros et al., 2021). These precise representations allow for accurate simulations of design variations and their impact on performance, enabling optimization of structures before actual printing. This reduces material waste and improves final product quality. For example, as highlighted in (Rachmawati et al., 2023), early failure detection in FDM 3D printers through Lightweight Convolutional Neural Networks (LCNN) and Digital Twin (DT) integration demonstrates the role of sensor data-driven fault diagnosis and real-time monitoring in ensuring high print quality while reducing errors and material waste.

DTs also facilitate process simulation by identifying potential issues such as warping or layer adhesion problems, leading to fewer print failures and higher reliability. Moreover, real-time monitoring enabled by DTs provides immediate feedback and allows for dynamic adjustments, ensuring adherence to design specifications and improving overall print quality.

The application of DT technology extends significantly into 3D Concrete Printing (3DCP) (Wang et al., 2023). This technology supports structural analysis by simulating the behavior of 3D printed concrete structures under various load conditions, thus optimizing designs for strength and durability. Moreover, lifecycle management of 3DCP structures is greatly enhanced through the use of DTs. By maintaining a digital twin of a structure, it is possible to monitor its performance over its entire lifecycle, track degradation, predict maintenance needs, and ultimately extend its lifespan.

Recent advancements illustrate the efficacy of DTs in improving 3DCP processes. Corradini and Silvestri (2022) developed a framework using a DT model to analyse 3D printing accuracy. This model enables real-time monitoring to halt the printer if deviations occur and employs post-printing analysis with Cloud Compare software to measure deviations between printed and ideal models, thereby calculating accuracy and identifying errors for future improvement. As emphasized in (Sokolov et al., n.d.), the potential of DTs in 3D Concrete Printing (3DCP) to enhance robustness, reliability, and scalability is explored, proposing architectures and methods to address unique challenges in integrating DTs into 3DCP workflows.

A novel DT ecosystem introduced by Pantelidakis et al. (2022) enables testing, process monitoring, and remote management in a virtual environment. This system integrates an open-source 3D printer web controller with the Unity 3D platform, consisting of data acquisition and processing components and a virtual representation component for continuous synchronization (See Figure 1). As detailed in (Rojas & Hasanzadeh, n.d.), insights into DT architectures for 3DCP demonstrate their capability to address the digitalization gap in construction by integrating layers such as sensing, communication, and control for lifecycle management.



State: Printing
Time elapsed: 5417s
Filament:

Current: 214.84°
Target: 215°C

Current: 55.76°C
Target: 55°C

File: Max_Measurement_Cube.gcode, path:
File Position: 27991
Estimated time left: 245777s
Progress: 0.943%

Figure 1: The 3D printer and its stateful DT in unity engine (Pantelidakis et al., 2022).

Additionally, advancements in integrating DTs with parametric design and numerical simulation approaches, as highlighted in (Nguyen-Van et al., 2023), further enhance construction optimization. This integration ensures the realization of complex designs and facilitates process optimization. This integration leverages predictive modeling and machine learning within DT-based 3DCP processes, emphasizing the potential for overcoming data scarcity through cyber-physical systems and simulation tools.
The development of freeform concrete panels exemplifies the innovative applications of DT in 3DCP. As demonstrated in (Meibodi, n.d.), the combination of robotic 3DCP and CNC Dynamic Bed Devices (DBD) for freeform panel production showcases the potential of DTs in achieving geometric fidelity and optimizing fabrication processes. This research underscores the significance of integrating DTs with advanced hardware configurations to produce highly detailed and waste-free structures. Overall, the integration of DT technology within 3DCP continues to demonstrate transformative potential, driving advancements in construction automation, efficiency, and sustainability.

Overall, the integration of DT technology in 3DCP demonstrates significant potential in optimizing design, improving process reliability, and enhancing lifecycle management, thereby advancing the industry towards the goals of Industry 5.0 (Ali et al., 2022). Current simulation methods for predicting the properties of 3D printed structures frequently concentrate on forecasting distortions and shape changes based on design and temperature distribution (Kantaros et al., 2021). These capabilities underscore the transformative impact of DT technology in the ongoing evolution of 3D printing and 3DCP. However, future research should focus on enhancing the interoperability and standardization of DT systems to further drive innovation and efficiency in AM.

2.3 Artificial Intelligence in 3DCP

The integration of DT technology and Artificial Intelligence (AI) into 3DCP represents a significant advancement in the field. These technologies enhance the efficiency, accuracy, and scalability of AM processes. For instance, Naser (2022) developed an AI-enhanced framework that incorporates a machine learning algorithm into a digital twin, allowing operators to identify concrete mixtures vulnerable to extreme service loads or environmental conditions.

AI has been applied in various areas of 3DCP, notably in rheology, which is crucial for controlling concrete properties. Nazar et al. (2022) demonstrated that Machine Learning (ML) algorithms can accurately forecast plastic viscosity and yield stress, thereby enhancing the prediction of concrete's rheological parameters.

Additionally, some works have utilized the results of the Unconfined Uniaxial Compressive Test (UUCT) to feed AI models for predicting the buildability of printed mortar and cylindrical printed bodies. Pott et al. (2022) focus on evaluating UUCT to study the evolution of material properties of printable mortar during early stages, including the determination of the static Young's modulus and distinguishing between ductile and brittle behaviors. In this paper, two failure modes are distinguished: material yielding and instability. Ivanova et al. (2022) propose an equation that utilizes Young's modulus to determine the maximum number of layers before stability failure in a hollow cylindrical printed body. This equation is then applied to evaluate the buildability property in the numerical simulation. Additionally, the Mohr-Coulomb criterion is employed to model the results of the UUCT test.

Moreover, Deep Learning (DL) techniques such as Artificial Neural Networks (ANN) have been employed to predict the properties of new concrete mixtures. For instance, Charrier and Ouellet-Plamondon (2022) explored the use of ANN to predict the dynamic yield stress and mini-slump behavior of cementitious materials for 3DCP applications. They proposed an empirical relationship between dynamic yield stress and mini-slump, with ANNs trained to predict these properties based on the admixture proportions. The neural network model demonstrated promising results for forecasting the printability of new mixes by simulating yield stress and mini-slump behavior, confirming the applicability of ANN in optimizing 3DCP material properties for better performance in practical applications (Charrier & Ouellet-Plamondon, 2022).

In addition to material optimization, AI has been used to enhance print quality in 3DCP. Sergis and Ouellet-Plamondon (2022) used genetic algorithms to optimize the networks' hyperparameters and the Pareto optimization algorithm to control materials and dosages. ANN models have also been used to improve print quality by establishing the relationship between the formation of extrudate and the printing parameters, utilizing historical data from 3DCP projects for training (Lao et al, 2020).

Beyond material and process optimization, AI techniques in 3DCP also extend to the real-time adjustment of printing operations, ensuring that printed structures meet desired specifications and performance criteria. Liu et al. (2024) demonstrated the successful integration of machine learning models, including ANN and support vector machines (SVM), to predict the mechanical properties of 3D-printed concrete. These models allowed for the real-time optimization of printing parameters, improving the consistency and quality of printed structures (Liu et al., 2024).

AI's potential to predict the mechanical properties of 3DCP, such as compressive strength, has been well-documented in the literature. Studies have utilized various machine learning algorithms, including decision trees, ANN, and SVM, to forecast compressive strength based on the features involved in 3D printing concrete. For example, Ghasemi et al. (2023) used machine learning algorithms, including XG-Boost, Random Forest, and multilinear regression, to predict the compressive strength of 3DCP (Ghasemi & Naser, 2023). Their results revealed that XG-Boost outperformed other models. In another study, Singh et al. (2024) demonstrated that ANN models provided more accurate predictions for the rheological properties of concrete compared to traditional regression methods, highlighting the advantages of AI in handling complex, nonlinear relationships within 3DCP datasets (Singh et al., 2024).

Moreover, Gao et al. (2024) applied a variety of AI models, including XG-Boost, ANN, and Random Forest, to predict the rheological properties of 3DCP, such as plastic viscosity and yield stress (Gao et al., 2024). Their study used a Taylor chart to compare the performance of different models, showing that the ANN model delivered the best results in terms of prediction accuracy. This aligns with the findings of Yao et al. (2023), who reported that BPNN (Backpropagation Neural Network) and Random Forest models exhibited strong predictability for compressive strength when applied to smaller datasets (Yao et al., 2023).

The integration of AI in 3DCP not only optimizes the material properties and process parameters but also enhances the overall reliability and efficiency of the printing process. This synergy between DT and AI enables the real-time adjustment and control of 3DCP operations, ensuring that the printed structures meet the desired specifications and performance criteria.

However, despite these advancements, several challenges remain. The complexity of integrating AI with DT systems, the need for extensive datasets to train AI models, and the requirement for high computational power are significant hurdles that need to be addressed.

2.4 Topological optimization

Another challenge is to reduce the weight and decrease the amount of material used while keeping the product functions (mechanical, usage, etc.). Topology optimization is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions, so that the resulting layout meets a prescribed set of performance targets (Bendsoe and Sigmund, 2003). Using topology optimization, engineers can find the best concept design that meets the design requirements while reducing the weight of the structures. Many complex geometries are feasible in additive manufacturing. The implementation of topological optimization in a model leads to a new internal structure while maintaining certain conditions (mechanical, design shape, functions, etc.).

Numerous studies have demonstrated the benefits of topology optimization in various industries. For instance, in aerospace engineering, topology optimization has been widely used to design lightweight components such as aircraft brackets, wings, and engine parts, significantly reducing weight while maintaining high mechanical performance (Zegard and Paulino, 2016). Similarly, in the automotive industry, topology optimization has been employed to redesign structural elements like chassis and suspension components, achieving material savings and enhanced energy absorption during collisions (Rozvany, 2009). As building designs become more extreme, such as taller structures or longer spans, architects increasingly rely on structural engineers for input on building geometry (Zegard et al, 2020).

In architecture and civil engineering, topology optimization has enabled the creation of efficient structural systems. Applications include the optimization of trusses and beams in bridges, as well as lightweight and efficient roof structures for large-span buildings (Duarte and Ferreira, 2013). Furthermore, in energy applications, optimized designs have improved the performance and material efficiency of wind turbine blades and heat exchangers (Sigmund and Maute, 2013).

These diverse applications underline the potential of topology optimization as a critical tool for innovative and sustainable design across multiple domains. However, integrating topology optimization with structural concrete design is challenging due to concrete's nonlinear material behavior (Stoiber et al, 2021). The integration of advanced computational tools with emerging manufacturing technologies continues to expand the scope and impact of topology optimization.

3. MATERIALS

3.1 Concrete and reinforced materials

The concrete or mortar mix for 3D printing needs to have good printability, which can be improved by adjusting powder mixtures and additives. Preparing concrete for large-scale 3D printing is complex, as many factors affect its fresh and hardened properties (Ma et Wang, 2018).

The printable concrete mixture needs to maintain suitable flowability, extrudability, buildability, sufficient strength, and minimal shrinkage. Increasing the cement content is a common approach to meet these requirements, but it leads to inevitable shrinkage due to cement hydration heat. To address this, replacing some cement with mineral powders is widely practiced. These powders possess good cementitious properties and pozzolanic reactivity, offering benefits such as reduced hydration heat, lime consumption, formation of hydration products, and improved physical and mechanical properties (Mazloom, Ramezanianpour, et Brooks, 2004; Aqel et Panesar 2016).

Recent advancements highlight the use of nanomaterials like nano-silica and nano-clay, which have demonstrated potential to improve the rheological properties, mechanical strength, and durability of 3D printed mixtures (Wu et al., 2023). Additionally, superplasticizers and viscosity-modifying agents tailored for 3D printing have been developed to achieve optimized flowability and shape retention without compromising buildability (Zhang et al., 2023).

The sustainability of 3D Concrete Printing (3DCP) mixtures is assessed with respect to economic and environmental impacts. Incorporating industrial wastes as supplementary cementitious materials (SCMs) offers significant sustainability and durability benefits in traditional concrete (Dey et al. 2022). Among these materials, fly ash, a byproduct of coal combustion in power plants, can be integrated into 3D printing to produce lightweight structures with improved workability and reduced permeability, such as architectural elements. Ground Granulated Blast Furnace Slag (GGBFS), generated from the iron manufacturing process, can enhance the strength and durability of 3D printed concrete structures, making them suitable for heavy-duty applications like bridges. Silica fume, a byproduct of silicon metal or ferrosilicon alloy production, can be added to 3D printed concrete mixes to increase compressive strength and reduce permeability, as seen in high-rise structures. Rice husk ash, produced from burning rice husks, a byproduct of rice milling, can be used as a partial replacement for cement in 3D printing to enhance sustainability and reduce environmental impact, such as non-load-bearing partitions and insulation panels. Metakaolin, produced by calcining kaolin clay, a byproduct of the ceramic or paper industries, can enhance the early-age strength development of 3D printed concrete, allowing for faster construction cycles, particularly for repairs or renovations. Glass powder, obtained from waste glass recycling processes, can be incorporated into 3D printed concrete to enhance aesthetic appeal and create translucent or light-transmitting elements, such as aesthetic components. Waste ceramic powder, generated from discarded ceramic materials, can be used as a filler material in 3D printed concrete to improve mechanical properties and reduce material costs, such as in structural components. Alumina refinery waste, a byproduct from aluminium refining processes, can be utilized in 3D printing to enhance the chemical resistance and durability of concrete structures, particularly in aggressive environments like marine infrastructure. Recent studies also demonstrate the potential of biochar, derived from agricultural waste, as a lightweight additive to improve thermal insulation properties in 3DCP (Huang et al., 2024). These industrial wastes can significantly enhance the properties of 3D printed concrete while also contributing to sustainability.

Additionally, the integration of steel reinforcement into 3D printed concrete structures is characterized by slower technological progress (Asprone et al. 2018). We can mention the Mesh Mould method, using digitally fabricated metal wire formworks for permanent reinforcement, or the use of synthetic or natural fibres in printable mortars.

The efficient construction of 3DCP includes the advantages of natural fibres such as eco-design and enhanced impact, thermal, structural, and fire performance compared to synthetic fibres. Natural fibres such as hemp, flax, jute, sisal, and coir are a new- class of materials, which have excellent potential in concrete mixtures (Lee et al. 2005). In particular, bio-based reinforcement strategies, such as lignin-coated fibres, have gained attention for their ability to improve bonding and reduce water absorption in 3D printed elements (Khan et al., 2023). Moreover, advancements in automated fibre placement technology now allow precise integration of natural fibres during the printing process, improving uniformity and reducing variability in mechanical properties (Gupta et al., 2023).

Hence, in order to enhance the tensile strength of these, natural fibres have to fit perfectly with the source material. Functionalized materials with biobased fibres can help decrease the cracking effect from shrinkage in anti-cracking screed mortar (Pons Ribera et al. 2022).

3.2 Advanced structured materials

The advanced structured materials are based on a static definition of complex shapes or on a material's combination to achieve one or more properties that respond to a predefined functionality, like that of a smart material (Julien Gardan 2019). Moreover, an astatic definition of complex shapes or material combinations provides a solid foundation for designing materials with enhanced durability, strength, or flexibility. By precisely engineering the structure and composition of materials, researchers can optimize their performance for different applications, ranging from structural elements in buildings to infrastructure components like bridges.

For example, research suggests using cement-free mineral foams derived from industrial waste as they demonstrate significant potential in reducing the required amount of concrete in composite structures (Figure 2). Additionally, this foam explores the impact of various print path schemes on the thermal insulation and compressive strength of printed parts (Bedarf et al. 2024).

3.3 Responsive materials – 4D Printing

Responsive materials are based on the 4D Printing process, which demonstrates a radical shift in Additive Manufacturing. 4D Printing (4DP) adds the concept of change in the printed configuration over time, depending on environmental stimuli (Choi et al. 2015). The application of 4DP technology in civil engineering, though in its nascent stages, promises groundbreaking advances in the field. While 3D printing (3DP) technology offers the advantage of fabricating intricate geometric designs, 4DP takes it up a notch higher by incorporating the element of transformation over time, facilitating self-assembly and response to environmental stimuli (Firoozi et Firoozi 2023). 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 (Julien Gardan 2019). This review did not find significant results in 4DP for construction and building.

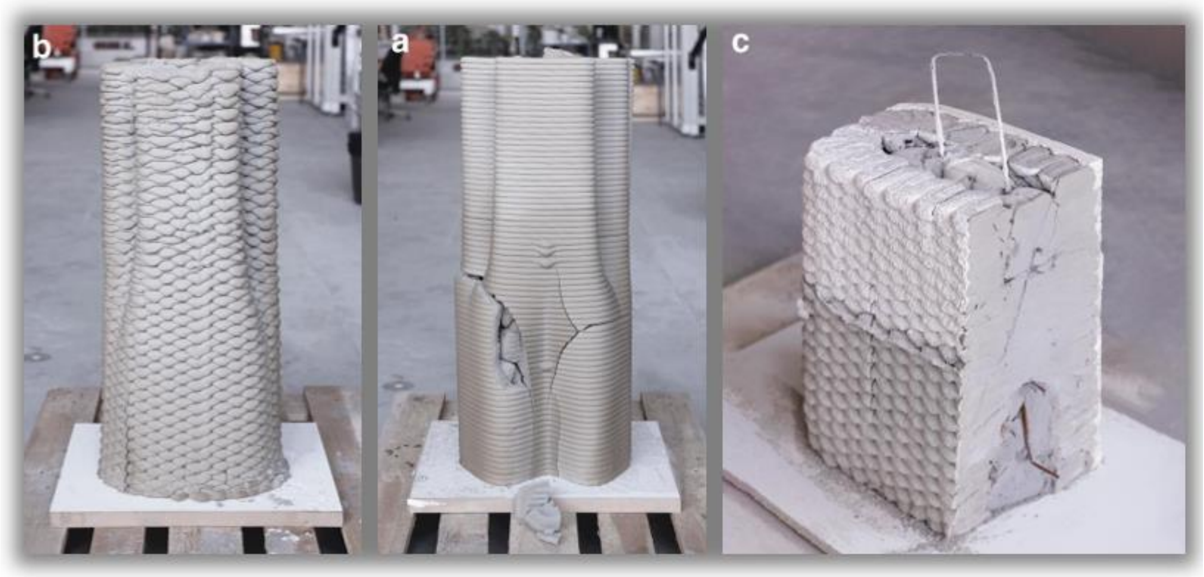


Figure 2: Print path prototypes: (a) single-wall contour shell design, (b) contour-perpendicular zigzag shell, and (c) a cut specimen combining a printed shell with cast infill, including rebar and sprayed plaster cover (Bedarf et al. 2024).

3.4 Economy

The housing crisis and major infrastructure projects are driving increased demand in the construction sector on a global scale. Many stakeholders believe that 3D printing in the construction sector could be a solution to address these challenges. Moreover, researchers indicate that incorporating 3D printing technology in construction reduces material usage and minimizes construction waste, potentially lowering construction expenses (Pessoa et al. 2021; Schuldt et al. 2021). However, the presence of a higher cement proportion in 3D printing materials for construction raises material costs, challenging the assumed cost reduction. Additionally, the significant cement usage contributes to environmental concerns due to its carbon dioxide emissions and high energy demands during production.

Emerging projects in civil engineering with additive manufacturing are gaining attention from the first initiative of Shanghai WinSun Decoration Engineering Company (WinSun n.d.) in 2014. This company specializes in printing individual components off-site, which are then assembled on location. Notably, these concrete houses can be built within a single day using 3D printing technology, with construction costs estimated at approximately $3800. The 3D printer developed by this Chinese group surpasses conventional systems in size and leverages the same Fused Deposition Modelling (FDM) technology. Impressively, it has demonstrated its capabilities by constructing ten houses in less than 24 hours. The manufacturer describes a printer towering at 6.6 meters (22 feet) in height, 10 meters (33 feet) in width, and 32 meters (105 feet) in length. Other companies established include ICON, COBOD, Apis Cor, Mighty Buildings, XtreeE, or BatiPrint3D.

Additionally, a digital twin presents many advantages, such as minimizing expensive trial-and- error optimization to save time and money, shortening the path for product qualification, and reducing defects.

Studies are limited in robust experimental validation and real-world implementation for advanced material combinations and printing techniques, limited exploration of 4D printing's applicability in civil engineering, insufficient economic feasibility studies addressing high cement content in 3DCP materials, and minimal integration of digital twin technology in optimizing the full lifecycle of additive manufacturing in construction.

4. AM TECHNOLOGIES FOR CONSTRUCTION

4.1 Extrusion technologies

This section presents the extrusion technologies used in civil engineering with a classification from (Julien Gardan 2016). AM extrusion technologies have their own design and manufacturing constraints related to the printing method, chosen material and expectations (aesthetic, mechanical behaviour, usage, etc.). Also known as 3DCP, the extrusion-based Additive Manufacturing is similar to FDM (Fused Deposition Modelling) or FFF (Fused Filament Fabrication), which uses a thermoplastic filament by fused depositing. FDM was invented in the 1980s by Scott Crump (Crump 1992) and trademarked by Stratasys Inc. The similar technical term is Fused Filament Fabrication (FFF). The filament is extruded through a nozzle to print one cross-section of an object, then moves up vertically to repeat the process for a new layer. The extrusion process can classified into three types: fused deposition, piston deposition and screw deposition (J Gardan et Roucoules 2014) (Figure 3).

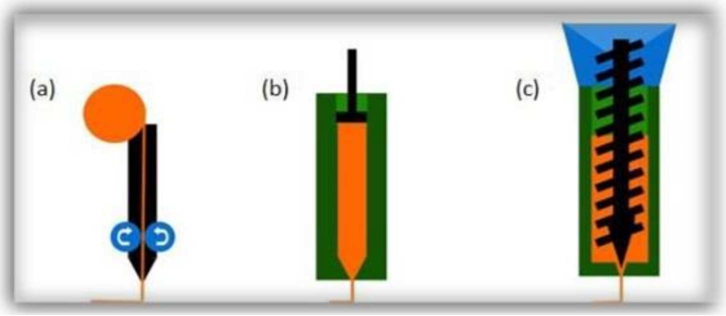


Figure 3: (a) fused deposition, (b) piston deposition, (c) screw deposition (J Gardan et Roucoules 2014).

4.2 Fused Deposition

Fused Deposition Modelling (FDM) is a layer- based additive manufacturing (AM) process that uses a thermoplastic filament deposited by fusion. FDM was trademarked by Stratasys Inc in the late 1980s and the equivalent term is Fused Filament Fabrication (FFF). The filament is extruded through a nozzle to print one cross-section of an object, then moves up vertically to repeat the process for a new layer (Figure 3). The most used materials in FDM are ABS, PLA and PC (Polycarbonate), but you can find out new blends containing wood and stone as well as filaments with rubbery characteristics. To predict the mechanical behaviour of FDM parts, it is critical to understand the material properties of the raw FDM process material, and the effect that FDM build parameters have on anisotropic material properties (Ahn et al. 2002). The support material is often made of another material and is detachable or soluble from the actual part at the end of the manufacturing process. The disadvantages are that the resolution on the z-axis is low compared to other AM processes, so if a smooth surface is needed a finishing process is required and it is a slow process sometimes taking days to build large complex parts (Kaufui V.Wong; Aldo Hernandez 2012). The filament structure can be strengthened by incorporating synthetic or natural fibers, enhancing its mechanical properties like a composite material (Deb et Jafferson 2021; Hedjazi et al. 2022). FDM technology is the most popular among desktop 3D printers and the least expensive professional printers. The FDM technology was invented in the 1980s by Scott Crump (Crump 1992; 1994).

4.3 Robotic arm

Robotic arm concrete printers typically include a print head mounted on a robot, along with peristaltic pump(s) and a mixer for the premix, all separate from the robot arm (Puzatova et al. 2022; Raghavan, Neethu, et Joy 2017). The mortar premix, engineered with pumpable rheological traits including fine particle distribution, low critical shear stress, and slow hardening, is stored in a shear mixer to prevent premature hardening due to thixotropic properties. This premix is then pumped by a peristaltic pump to a mixing auger within the print head, where additives are introduced to expedite mechanical property development post-extrusion (Figure 4). Autonomous mobile robotics in building construction open opportunities for in situ Additive Manufacturing (AM) (Dörfler et al. 2022). Mobile 3DCP systems tailored for on-site construction have the potential to offer a more flexible work area by leveraging mobility. Consequently, this opens up new possibilities in architecture for the production of building components exceeding the static limitations of conventional systems. By addressing challenges such as material handling, printing precision, and on-site mobility, these systems pave the way for innovative architectural designs and construction techniques.

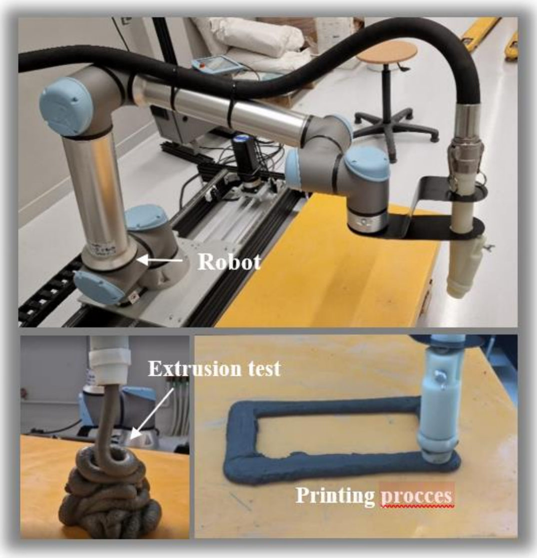


Figure 4: Photograph of robotic arm used for concrete 3D printing at ESTP, Troyes.

4.4 Gantry system

The innovative 3DCP construction process offers increased sustainability by employing an extrusion-based Additive Manufacturing technique utilizing conventional construction materials such as concrete (Bos et al. 2016; Duballet, Baverel, et Dirrenberger 2017). Contour Crafting (CC) is an extrusion-based AM technology invented by Khoshnevis (Khoshnevis 2004) from the University of Southern California and has been in development since 1998 (Figure 5). The technology was specifically designed for on-site construction automation. The printer is therefore installed on a large overhead gantry frame (Figure 6), which can be quickly setup (Zhang et Khoshnevis 2013). CC uses a combination of extrusion and filling process. The extrusion nozzle uses a side and top trowel for a smoother surface and constant top finishing. The current resolution of 3DCP can be achieved using a 3-axis gantry system.

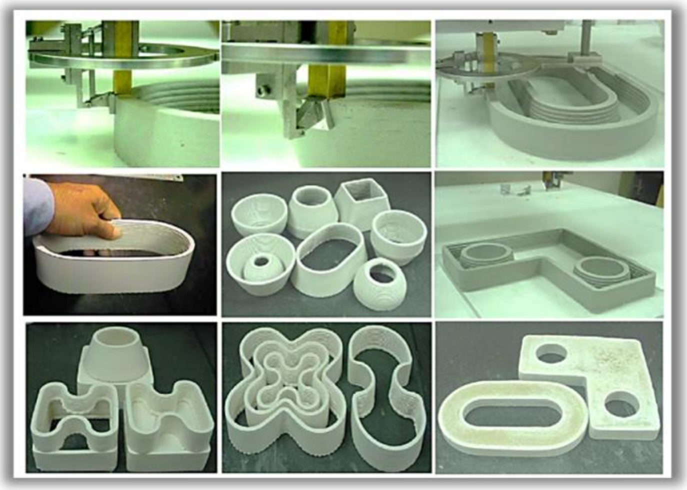


Figure 5: CC in operation and representative 2.5D and 3D shapes and parts filled with concrete (Khoshnevis 2004).

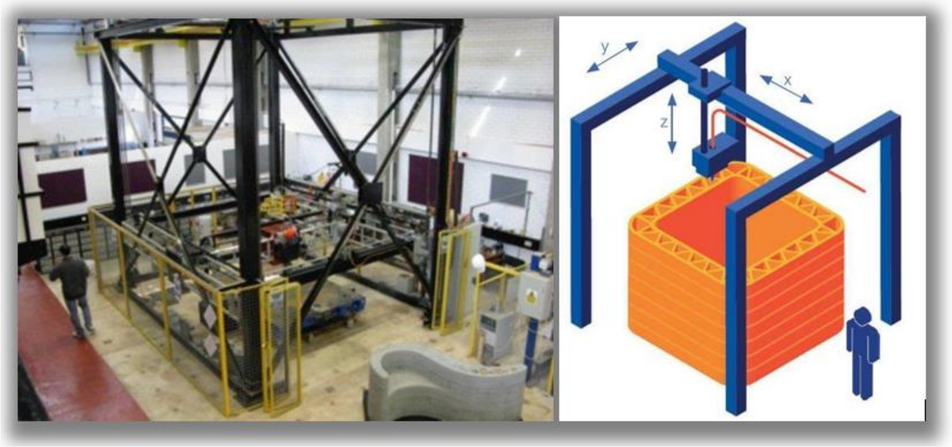


Figure 6: Three-axis gantry printing system of 3D Concrete Printing at Loughborough University - 5m (W) x 5m (L) x 6m (H) (Lim et al. 2016) & Schematic representation of gantry system.

4.5 Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) is a popular technique known for its speed and cost- effectiveness. LOM is a 3D Printing technology for creating 3D solid objects via sheet lamination (Diamond et al. 1998; Mekonnen, Bright, et Walker 2016). Studied since the 1980s, LOM can produce complex geometrical parts. Stratoconception® is classified within the sheet lamination category of additive manufacturing (AM) processes (Barlier 2004). It involves slicing the 3D model of the part into layers, known as strata, through computational methods. This technology demonstrates the potential for additive manufacturing to enhance timber or concrete architecture by overcoming existing limitations and creating high-value building components (Fréchard et al. 2023).

4.6 Discussion

Functionalizing materials through advanced structured materials or 4D printing will enhance building and construction through additive manufacturing. A challenge in 3D printing for building and construction is countering concrete's low tensile strength and ductility. Fiber reinforcement enhances the mechanical and thermal properties of regular concrete, improving compressive, flexural, and fracture characteristics (Lu, Xiao, et Li 2024; Singh et al. 2023). Building on these improvements, the research explores combining AM with fiber reinforcement, which can mitigate negative impacts, especially in tensile and flexural resistance. Introducing natural or biobased fibers is expected to optimize mechanical properties and reduce carbon emissions. Studies lack of comprehensive comparative analysis among different extrusion technologies (FDM, robotic arms, gantry systems, and laminated object manufacturing) in terms of scalability, precision, and material compatibility, insufficient exploration of hybrid systems that combine these technologies for optimized construction, and limited experimental validation for their practical application in real-world civil engineering projects.

The high initial investment required for AM equipment and infrastructure may limit its accessibility and adoption, particularly for smaller construction firms or in developing regions.

5. NEW TRENDS IN ADDITIVE MANUFACTURING

5.1 Remote housing

3DCP offers a potential solution to address remote housing challenges. Milad Bazli & al examine remote housing construction challenges, particularly in the Australian Northern Territory (NT), and discuss the feasibility and efficiency of employing concrete 3D printing to address them (Figure 7). They outline the advantages, limitations, and concerns associated with 3DP for remote housing, alongside showcasing completed projects. Findings suggest that evaluating factors like materials, design, process efficiency, logistics, labour, and environmental impact is crucial to determine the practicality of 3D printing in remote areas. Using local materials meeting printability, buildability, and robustness criteria could make 3DCP a cost-effective solution. However, decision-makers must consider options such as remote on-site fabrication, local material availability and quality, and the limitations of concrete 3DP when comparing its feasibility to conventional methods (Bazli et al. 2023). Other studies of 3D-printed construction in remote, isolated, and expeditionary settings were realized. Suggestions include exploring the printing of full-scale structures and components using locally available materials in uncontrolled environments, establishing standards for 3D printing, automating additional construction processes, and conducting environmental impact and cost life-cycle analyses (Schuldt et al. 2021).

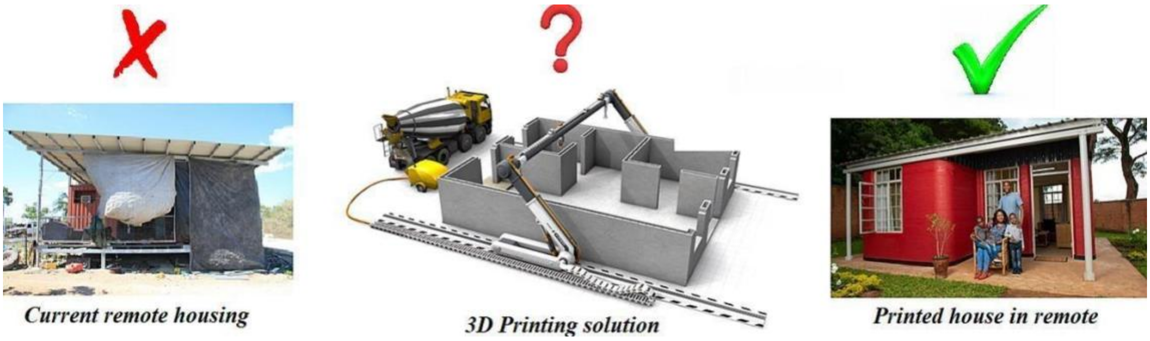


Figure 7: Concrete 3D printing as a solution to overcome remote housing (Bazli et al. 2023).

5.2 Mesh mould

A large 6-axis robot to extrude thermoplastic polymer is used to shape a formwork (Hack et Lauer 2014). In this application, the structures serve as reinforcement for concrete. Concrete is poured over the formwork and manually smoothed (Figure 8). This method reduces fabrication time for complex structures, making large-scale applications feasible. Mesh density can vary based on forces acting on the structures. The mesh enhances concrete's tensile strength, potentially replacing traditional steel reinforcement. A large 6-axis robot for thermoplastic polymer extrusion to shape formwork offers advantages such as faster fabrication times, flexibility in design, and improved structural performance. By optimizing mesh density and integrating the formwork into the concrete construction process, this method presents a promising approach to efficient and sustainable building construction.

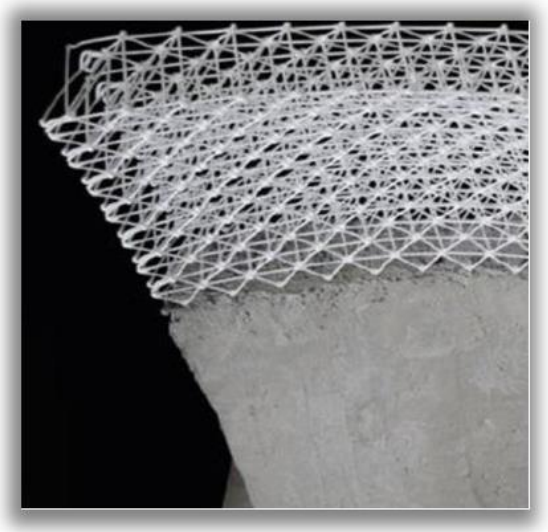


Figure 8: Mesh mould as concrete formwork.

5.3 Timber wood construction

Stratoconception® emerges as a potential new construction solution, providing access to the creation of objects with complex morphologies. It relies on simple technical and material means mastered by the timber construction industry. Within the Houot company in France, a part of the pavilion envisioned by students from the School of Architecture in Nancy (France) was designed for the French Rowing Federation for the 2024 Paris Olympics. The structure combines wood reuse and innovation by incorporating Stratoconception® technology (Figure 9). Stratoconception® represents a promising advancement in construction technology, offering the ability to create complex structures using sustainable materials and innovative fabrication techniques.

Figure 9: Connection or assembly by Stratoconception® for timber construction.

5.4 Architecture

Currently, architecture is adapting to address social and environmental concerns by adopting a more resilient approach. A key aspect of this adaptation is embracing temporariness as a solution. Rather than the traditional high-density approach to urbanization, there's a shift towards low-density design strategies, particularly in printed architecture (Paparella et Percoco 2023).

In 2012, Massimo Moretti co-founded WASP (World's Advanced Saving Project) with a team of young designers. WASP designs, manufactures, and distributes 3D printers made in Italy globally. Moretti drew inspiration from nature, particularly the Potter Wasp, which constructs its nest using materials with TECLA—Technology and Clay project by MCA—Mario Cucinella Architects and WASP (Moretti 2023). In 2019, WASP focused on producing large 3D printers capable of building houses with natural materials sourced locally (Figure 10).

House 3D printing expends their function through bioclimate architecture with high-performing passive material, with early findings showcasing the potential of integrating 3D printing of mud (Dubor, Cabay, et Chronis 2018). Adopting temporariness in architecture responds to social and environmental concerns, aiming for resilient built environments. This shift from high-density urbanization to low-density designs, especially in printed architecture, offers advantages like resource efficiency, flexibility, and resilience. However, challenges such as infrastructure costs, transportation issues, and land use must be addressed in low-density strategies.

Figure 10: 'Here and Now,' instant architecture. TECLA—Technology and Clay is a project by MCA—Mario Cucinella Architects and WASP (a ©WASP, b, c ©Iago Corazza).

6. STANDARDS IN ADDITIVE MANUFACTURING

The purpose of additive manufacturing (AM) technology standards is to enhance the construction industry's knowledge base, stimulate research, and promote the adoption of innovative technologies. These standards are essential for defining terminology, evaluating the performance of various production processes, ensuring the quality of final products, and outlining the calibration procedures for additive manufacturing machines (ASTM, n.d.). Recently, the International Organization for Standardization (ISO) has established significant standards in this domain, including ISO/ASTM 52939:2023, which specifies quality assurance requirements for additive construction (AC) projects. This standard ensures consistent quality in building and construction projects utilizing AM techniques, regardless of the materials and processes employed. Another important standard is ISO 17296-2:2015, which outlines the fundamental processes of AM, detailing existing technologies and the variety of materials used in these processes. Additionally, ISO 17296-3:2014 addresses the principal testing requirements, including key quality characteristics of AM parts, suitable test procedures, and recommendations for ensuring quality. Furthermore, ISO/ASTM DIS 20195, titled "Standard Practice – Guide for Design for AM," has been under development since 2015 and aims to consolidate best practices in design to ensure the reliability and performance of AM products.

7. DISCUSSION AND OVERVIEW

Many studies and applications demonstrate limited experimental validation and real-world implementation of advanced 3D printing techniques in diverse and uncontrolled environments. They also show insufficient comparative analysis of different methods and materials regarding scalability, cost-effectiveness, and environmental impact, a lack of standardization and lifecycle assessments for emerging technologies, and minimal exploration of hybrid systems and low-density architectural designs to address broader social, environmental, and logistical challenges in construction.

The table below provides a comprehensive overview of additive manufacturing technologies, materials, and their applications in the construction industry. It highlights various advanced techniques such as 3D Concrete Printing technologies, which enhance design flexibility, real-time monitoring, and optimization. It also emphasizes the integration of artificial intelligence (AI) to improve efficiency and predict material properties. Various materials, including thermoplastic filaments, concrete mixtures, and natural fibers, are detailed, showcasing their roles in creating complex structures, enhancing sustainability, and optimizing material usage. Applications range from constructing large-scale structures and architectural elements to enhancing lifecycle management and developing innovative construction solutions like remote housing and timber construction. The table underscores the transformative impact of these technologies on reducing costs, improving structural performance, and driving innovation in the construction sector.

Table 1: Overview of Additive Manufacturing Technologies, Materials, and Applications in Construction.

Technologies	***Materials***	***Applications***
Additive Manufacturing (AM)	Various materials including thermoplastic filament (ABS, PLA, PC), steel reinforcement, synthetic and natural fibers	Creating complex geometries, reducing time and cost in product development
3D Concrete Printing (3DCP)	Concrete, mortar, supplementary cementitious materials (SCMs) like fly ash, GGBFS, silica fume, rice husk ash, metakaolin, glass powder, waste ceramic powder, alumina refinery waste, steel reinforcement, natural fibers	Constructing large-scale structures, creating architectural elements, enhancing sustainability and durability, building remote housing
Robotic Arm	Concrete mixtures	Printing complex concrete structures on-site, enhancing flexibility in architectural design
Gantry System	Concrete mixtures	On-site construction automation, increasing sustainability in construction
Laminated Object Manufacturing (LOM)	Various sheet materials	Producing complex geometrical parts, enhancing timber or concrete architecture
Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM)	Thermoplastic polymer, concrete	Shaping formwork, reinforcing concrete structures, enhancing structural performance
Stratoconception®	Timber	Creating complex morphologies in timber construction, innovative fabrication techniques
Digital Engineering Support		
Generative Design	N/A	Creating new algorithms, modifying existing ones in a graphical scripting environment, generating curved-layered printing paths
Digital Twin (DT)	N/A	Simulation, analysis, real-time monitoring and optimization in 3D printing, lifecycle management of 3D printed structures
Artificial Intelligence (AI)	N/A	Enhancing efficiency, accuracy, and scalability in 3D printing, predicting properties of new concrete mixtures, optimizing material properties
Topology Optimization	N/A	Reducing weight and material usage in designs, optimizing material layout for specific loads and conditions

8. CONCLUSION

In the current era of the construction industry, Additive Manufacturing (AM) is emerging as a transformative force, promising revolutionary advancements. This technology provides a viable and sustainable alternative to traditional methods, offering tangible benefits such as waste reduction, enhanced design flexibility, and accelerated construction processes. Technologies such as 3D Concrete Printing (3DCP) pave the way for achieving complex shapes previously unattainable, enabling significant innovations in architectural and structural design.

An analysis of extrusion technologies highlights their adaptability to diverse materials, including cementitious mixtures enhanced with natural or synthetic fibers to improve mechanical performance and durability. Robotic and gantry systems also offer in-situ automation solutions, enabling flexible on-site construction and opening new opportunities for applications in remote areas or dense urban zones. However, environmental challenges, such as the high carbon footprint of commonly used materials, remain a critical concern.

Advanced structured materials, such as cement-free mineral foams and reinforced composites, have demonstrated potential to reduce concrete usage while optimizing the thermal and mechanical properties of printed elements. In parallel, responsive materials used in 4D Printing mark the beginning of a revolution in construction, enabling structures that can adapt to environmental stimuli. However, their practical application in civil engineering remains limited and requires further research.

The integration of Digital Twin (DT) technologies and Artificial Intelligence (AI) is a crucial lever for optimization. These tools enable real-time simulation, predictive analysis, and lifecycle management of printed structures, reducing errors and waste while enhancing the quality of final products.

To fully harness the potential of AM in the construction sector, interdisciplinary collaboration among architects, engineers, material scientists, and construction professionals is essential. Global standards, advanced simulation methods, and long-term environmental impact assessments must be developed to ensure the sustainable and efficient application of these technologies.

The figure below illustrates the connections between the keywords and the analyzed articles, providing a representation of the significance of the topics addressed.

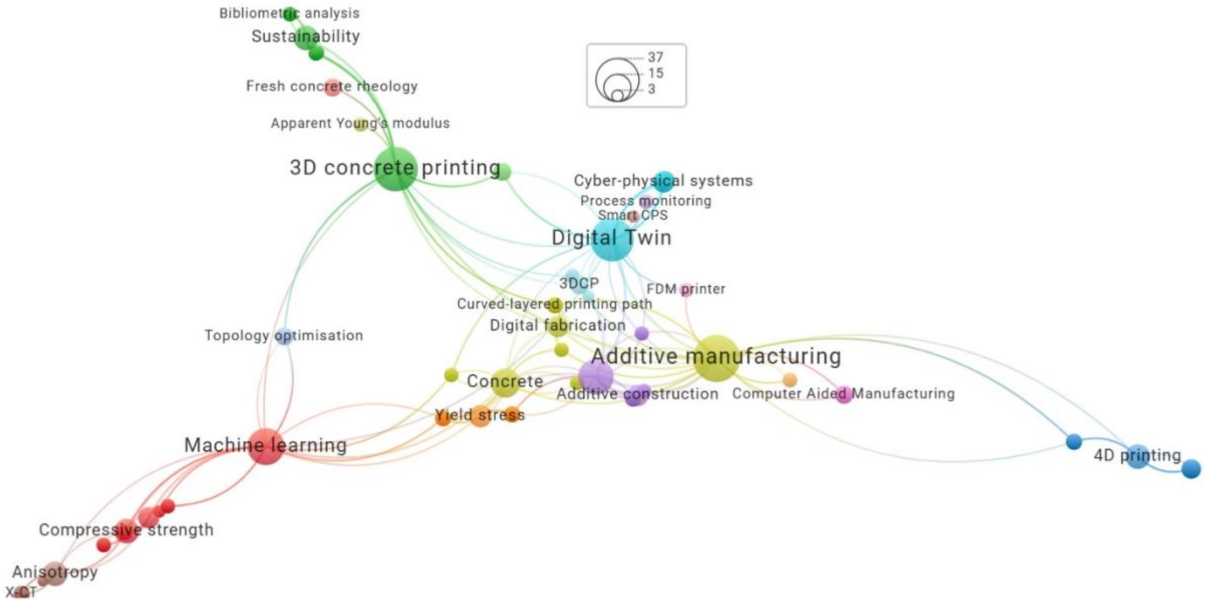


Figure 11: Visualizing bibliometric network of this review.

Ultimately, transforming the construction industry relies on harmonizing technological innovation with a holistic vision that accounts for environmental, economic, and social considerations. By combining rigorous scientific approaches with integrated perspectives, AM can become a cornerstone of a more sustainable, efficient, and resilient construction industry.

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