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Review Article

The Role of 3D Printing in Engineering and its Historical Perspective in Civil Engineering - A Review

V. Sundaram[1], Vidhya Lakshmi Sivakumar[2], Anand Raju[2], A. Saravanan[1], Titus Richard[1*]

[1]*Department of Biosciences, Saveetha School of Engineering, SIMATS, Saveetha University, Tamilnadu, India.*
[2]*Department of Civil Engineering, Saveetha School of Engineering, SIMATS, Saveetha University, Tamilnadu, India.*

**Corresponding Author : hodbiotech.sse@saveetha.com*

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***Abstract* - *Printing in three dimensions has opened the door to new practices and set new standards in a number of different industries, including Civil Engineering. Prototypes were the first step in the development of three-dimensional printing. Currently, it manufactures specialized concrete formwork, state-of-the-art structural components, and accurate scale models for the construction of structures. In this study, the literature review is carried out for the multi-disciplinary use of 3D Printing, and the major focus is on 3D Printing in Civil Engineering. This technology has the potential to improve design flexibility as well as efficiency on construction sites, which could result in changes to building practices in Civil Engineering. This may revolutionize building. The field of Civil Engineering is gradually gravitating towards the use of 3D Printing technology because of substantial investments in research and development. Printing in three dimensions has enabled the construction of bridges and structures, in addition to other novel ideas. The conventional notion is challenged by these principles, which also make it possible to construct infrastructure that is beneficial to the economy, the environment, and the public good. The broad application of three-dimensional printing in Civil Engineering is a game-changer since it guides in an era of innovation in the building of infrastructure. In conclusion, the use of 3D Printing in Civil Engineering will make it possible to create more complex designs and speed up construction. Using this technology, sustainable infrastructure might completely change the way things are currently done and significantly increase productivity.*

Keywords* - *3D concrete, 3D Printing technology, Historical perspective, Mixed-methods, Civil Engineering.

1. Introduction

The field of engineering has seen considerable advancements since the adoption of 3D Printing technology, which has radically revolutionised conventional methods and approaches. To properly comprehend the transformative potential of 3D Printing in Civil Engineering, it is essential to understand its dynamic character and historical background. An examination of the historical development of 3D Printing in Civil Engineering reveals both the notable progress made by the technology and its crucial role in reinventing material sciences and construction methods.

This inquiry highlights the need to understand the historical background in order to deal with the current environment and develop strategies for future improvements in the field of Civil Engineering. The integration of 3D Printing technology inside the construction industry has the potential to bring about a transformative paradigm change in the field (Al-Noaimat et al. 2023). In the face of environmental concerns and the imperative for sustainable industrial practices, a society may discover a ray of hope in the integration of 3D Printing technology with recycling methods.

The technology known as three-dimensional printing also referred to as additive manufacturing, has garnered significant attention in various industries due to its transformative impact (Olawumi et al. 2023). Construction and building use innovative methods and materials. In the construction process, "industrialization" refers to the gradual advancement and growth of construction technologies (Olsson et al. 2021). A growing array of industries, such as agriculture, medicine, automobile and locomotive sectors, aviation, and the aerospace industry, are increasingly using 3D Printing technology for mass production and customization of open-source designs (Shahrubudin, Lee and Ramlan, 2019). The utilization of 3D Printing technology facilitates the development and production processes of digital pharmaceutical products.

In recent years, there has been a notable increase in the utilization of 3D Printing technology in both the preliminary phases of medication research and the large-scale manufacturing of pharmaceutical products (Tracy et al. 2023).

An increasing number of individuals are adopting the utilization of 3D Concrete Printing (3DCP) as a means to mitigate the ecological consequences associated with cement production. Existing studies examining the sustainability benefits of 3D Concrete Printing (3DCP) have neglected to address the social impact of this technology and the influence of construction businesses' adoption on their performance. Extrusion-based Three-Dimensional Printing (E3DP) is commonly employed in the field of in vitro and situ bio fabrication, mainly owing to its cost-effectiveness and the wide range of biomaterials and cells that may be effectively utilized. A common modification of the traditional Extrusion-based 3D Printing (E3DP) method is the coaxial 3D Printing process.

This technique uses coaxial nozzles with an integrated network of microfluidic channels to achieve the simultaneous expulsion of many substances (Wang et al. 2023). One of the potential advantages of automating construction processes is the potential reduction in the workforce size of a building site. Other benefits, such as decreased construction durations and reduced production expenses, accompany this. The approach uses a substance referred to as 3D extruded cement composite. This unique type of concrete possesses the ability to be 3D Printed without the need for additional forms or formwork to be applied (Uhlík, Buch and Unčík, 2022). With the development of construction, 3D Printing is currently used for a wide range of printable materials.

As an alternative to cement, a mixture of fly ash and ground-up blast furnace slag can be used. Vessel viscosity, setting time, discharge, and flow were taken into consideration for the evaluation of 3D Printing. The 3D Printer can extrude specific viscoelastic pastes. The optimal spray flow rate was determined by water-cementitious ratio and combination to maximise print quality. C-A-S-H colloids produced printed specimens as strong as moulded ones in compression tests. Finally, cement-free mixed material for 3D Printing with industrial waste is recommended (Fiala et al. 2023). Rapid progress in the fields of 3D Printing and computer-aided design has led to the development of mechanical metamaterials that emulate the intricate patterns found in nature. These materials possess enhanced mechanical properties as a consequence of their microstructurally optimized attributes (Xiao et al. 2021).

2. Assess the Use of 3D Printing in Civil Engineering Using Existing Studies

The three studies mentioned above pertain to the domain of 3D Printing technology and its use in various domains within Civil Engineering. The initial study focuses on the formulation of low-carbon cementitious mortars designed explicitly for 3D Printing applications. To be more explicit, the study examines the feasibility of substituting Portland cement with Ground-Granulated Blast furnace Slag (GGBS). The investigation examines the feasibility and flowability of various mortar combinations, as well as the structural performance of a 3D-printed arch truss member, by conducting tests on a prototype truss. The second study used 3D Printing technology to fabricate rock samples with structural planes, aiming to examine the impact of discontinuities on the mechanical characteristics of rock formations.

This observation emphasizes the indistinguishable impact of constructed joints on the strength of rock masses, as well as the resemblance between natural and artificial rock mass joints. These two studies demonstrate the creative capacity of 3D Printing in Civil Engineering, whether it is used to create construction materials or simulate geological features to assess their influence on the stability of structures Youyu Wang et al. (2020). B. Suryanto et al. (2023) and J.C. Cámara-Molina et al. (2023).

2.1. Use-Limitation of Automation in Construction

The growing automation of construction operations provides a multitude of advantages in terms of accuracy and efficiency. Nevertheless, there are drawbacks, particularly regarding the incorporation of robotics into a wide range of intricate construction assignments. Some obstacles include the reliance on standardised designs, the inability of automated systems to handle abnormalities or unexpected changes in the building environment, and the need for continuous human monitoring and intervention in managing complicated tasks.

2.2. Performance Requirements of 3D-Printing Concrete Materials

For 3D-printed concrete materials to be efficiently used in construction, several performance criteria must be satisfied. These criteria incorporate architectural considerations such as precision, smoothness, and dimensional consistency, as well as mechanical characteristics, including robustness, longevity, and adaptability. Having a thorough comprehension of and following industrial standards for 3D-printed concrete materials is crucial in order to guarantee structural integrity.

2.3. 3D Printable Material Challenges

The challenge of creating 3D-printable materials that meet the demands of many applications remains unresolved. It is crucial to overcome problems such as improving material quality, addressing material compatibility issues, and determining the best material compositions for different printing processes. To overcome these obstacles, a significant amount of research is required to enhance the characteristics of materials and create new combinations of materials that can be used in 3D Printing.

2.4. Key Preparation Technology

An essential component of technologies for preparing 3D Printable materials involves the advancement of techniques and procedures that enhance the efficiency of substances for

3D Printing. This encompasses advancements in material compositions, manufacturing techniques, surface modifications to improve bonding and print quality, and assessments of compatibility. By overcoming obstacles related to material production, these technologies strive to enable the application of 3D Printing in real-world environments.

2.5. Worldwide 3D-Printed Construction

The rise of 3D-printed construction technologies is causing a significant shift in traditional building processes. Additive manufacturing and 3D LiDAR are technologies that have a substantial worldwide influence on architectural advancements, construction methods, and the safeguarding of cultural heritage. Their diverse impact showcases progress in international construction methods and technological improvements.

2.6. Printing Parameters

The manufacturing settings have a significant impact on the quality and performance of 3D-printed objects. The criteria mentioned above encompass the material properties, injector diameter, infill weight, layer height, and printing speed. To guarantee the durability, accuracy, and general excellence of 3D-printed items, it is crucial to understand and enhance these characteristics.

2.7. Historical Perspective

Historically, the progress made in 3D Printing technology within the realm of Civil Engineering exceeds any earlier achievements recorded in written literature. This paper presents a comprehensive examination of the development and origins of 3D Printing in Civil Engineering, demonstrating a trend that has resulted in better results compared to previous studies. The progress can be ascribed to multiple sources, including improved materials, advanced printing techniques, optimised design approaches, and a deeper comprehension of structural dynamics.

The integration of advanced computational tools with empirical study, experimentation, and iterative enhancements has resulted in improved outcomes and higher effectiveness. The historical development demonstrates a consistent pursuit of innovation, experimentation, and adaptation, leading to significant progress and breakthroughs in the application of 3D Printing in Civil Engineering, surpassing previously set standards documented in academic literature.

3. Evolution of 3D Printing Use in Civil Engineering

The subject of Civil Engineering has witnessed significant achievements as the utilisation of 3D Printing has experienced rapid growth. With the widespread availability of 3D Printing, numerous organisations across various industries have extensively utilised this technology for prototype purposes. Throughout the early 2000s, the company began to make progress in the field of Civil Engineering. Their initial concentration was on the production of accurate and scaled architectural prototypes. The task mentioned above was executed promptly at the commencement of the project. The building industry has increasingly prioritized the integration of 3D Printing as a result of technological advancements.

The ongoing transition towards the utilization of 3D Printing in Civil Engineering is currently being investigated by researchers with the aim of broadening its applicability in ecologically sustainable, extensive construction projects. The rapid development of 3D Printing technology has allowed it to be used for more than just making prototypes and visualizing designs. Now, it can also be used to make one-of-a-kind parts and complex structures. The crisis has severely impacted the building industry. Because of this, the construction industry has undergone a profound and far-reaching change.

This technique has been shown to be effective in producing load-bearing structural elements on the construction site, which facilitates the development of creative designs and raises the overall structural efficiency of buildings that already exist. By reducing waste and facilitating material repurposing, the application of 3D Printing technology in fields other than construction has the potential to promote environmental sustainability.

Table 1. Comparison between 3D Printing in general and Civil Engineering

Application	Use of 3D Printing in General	Application in Civil Engineering
Assembling	Small-scale component manufacturing	Producing complex structural parts in a workshop
Automotive	Production of unique pieces	Building viaducts and bridges
Art and Design	Producing intricately detailed works of art	Creating aesthetic components for building structures
Aerospace	3D Printing of lightweight parts	Constructing complicated buildings
Medical App.	Implants and prostheses fabrication	Developing specialised concrete formwork
Education	Practical instruction and demonstrations	Principles of structural design instruction

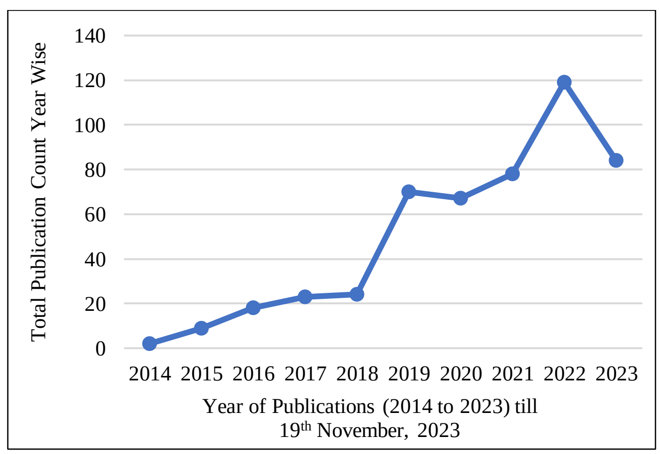
The application of 3D Printing technology to Civil Engineering represents a paradigm shift in the methods utilized in construction. As a result, it offers unmatched opportunities for efficiency and innovation. Three-dimensional printing was initially developed as a tool for prototyping, but it has swiftly gained traction and revolutionized the construction industry. Its capacity to create intricate and personalised buildings with unmatched accuracy is the source of this skill. Within the domain of Civil Engineering, numerous applications can be attributed to this discipline, including the expedited production of architectural prototypes, the fabrication of delicate building components such as walls and columns, and even the construction of entire edifices. This novel technique facilitates the construction process, reduces the amount of resources wasted, and enables the realization of intricate design concepts that were before unachievable.

The advent of 3D Printing has ushered in a transformative shift within the realm of Civil Engineering, introducing a novel era characterized by innovative and environmentally conscious approaches to construction. As a consequence of this significant shift, there has been a notable increase in the adoption of environmentally sustainable products, accompanied by a corresponding decrease in waste generation. This particular study focuses on the production of biopolymer slurries derived from byproducts of 3D Printing materials, with a specific emphasis on their potential applications in the field of sustainable building. The following study aims to investigate the feasibility of blending lignocellulosic waste fibres, particulates, and additives such as glycerol and water with xanthan gum in order to modify its fluidity qualities (Rech et al. 2022). The work describes an effort to find eco-friendly earth-based combinations for 3D Printing. This required creating 18 combinations of silica sand, rice husk, dirt, marble reject dust and natural fibres. The mixes underwent testing to evaluate their printability, shrinkage, flexural strength, and compressive strength.

Two optimal combinations can be utilized by a 3D Printer to manufacture construction bricks. The investigation revealed several combinations characterized by high strength and minimal shrinking. Lime and sisal emerged as the most optimal materials in terms of mechanical performance, cost-effectiveness, and carbon footprint. The blend in question exhibits a low embodied carbon content and possesses a compressive strength of 1.26 MPa. It is available for purchase at a price of 0.137 Euros per kilogram. Following the completion of full-scale printing, the enhanced mixture demonstrated a compressive strength of 11.04 MPa and a flexural strength of 1.26 MPa (Faleschini et al. 2023). Formerly to the one, this work examines the printing mixture in two distinct conditions: “fresh” (Mix 1) and “dry” (Mix 2). By demonstrating how the presence or absence of aggregates in the mélange affects the development of the cohesiveness trend, our research is notably original. This is especially crucial given that current 3DCP simulation methods are incapable of accommodating this behaviour. Concurrently, the author designed and built a uniaxial load stand, a novel apparatus utilized to assess a novel combination. In order to determine the rheological properties of Concrete produced through 3D Printing, experiments were performed using simultaneous sliding pipe, direct shear, and uniaxial stress methods. Although Mix 2 did not contain any ultrafine particles, the Bingham fluid properties of mix 1 were assessed (Vespalec et al. 2023).

This study contrasts industrial 3D Printing’s environmental impact with traditional building methods. Cradle-to-Gate LCA evaluates the construction, components, material, and environmental implications of 3D Printing (3DP). Kaolinite-based calcium sulfoaluminate cement concrete greens sizeable 3D Printing. This concrete has kaolin clay in its structure.

3D-printed KCSC walls have 12%, 55%, and 4% lower EP, EE, and GWP per volume than bricks. 3D-printed KCSC walls have 55%, 77%, and 53% lower EP, EE, and GWP per unit compressive strength, respectively. Replacement of the wall panel lowers Acidification Potential (AP) by 30% per volume and boosts compressive strength. KCSC walls manufactured in 3D have a lower environmental effect than traditional buildings (Abu-Ennab et al. 2022).



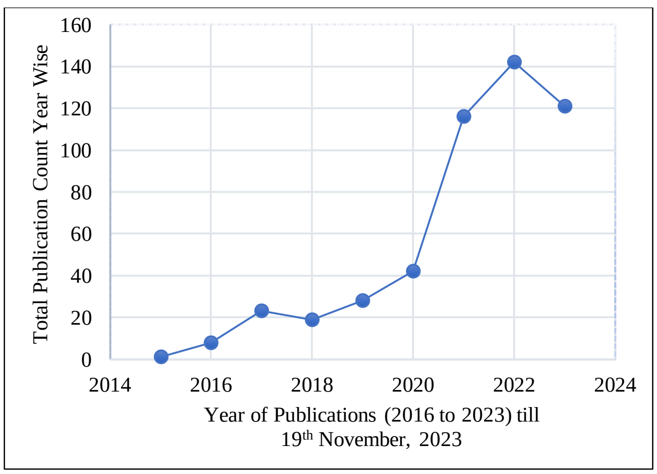
**Source: https://app.dimensions.ai*
Search Criteria: “3D Printing” and “Multi-Disciplinary”
Exported: 19/11/2023

This data is sourced from Dimensions at www.dimensions.ai.

Fig. 1 Publications based on the keywords “3D Printing” and “multi-disciplinary” 2014 to 2023 till 19th November 2023 data provided by Dimensions AI [45]

As per Figure 1, The Production of academic or educational resources increased considerably between 2014 and 2023. The amount of work generated increased steadily after two papers were published in 2014. In 2019, 70 papers were published, up from previous years. Paper publication output was steady in 2020 and 2021. There were 119 publications in 2022, a significant increase. With 84 publications in 2023, there was a significant fall from 2022. It is important to note that this number is still much more significant than prior years, indicating a dynamic scientific or informational environment. Publications increased consistently and significantly between 2014 and 2022. Despite significant modifications in later years, scholarly or instructional resource output is consistent and encouraging. As per Figure 2, In the year 2015, a solitary publication was recorded, suggesting a somewhat limited commencement.

An upward trajectory was observed in the number of papers that were published throughout 2016 – 2017, with a total of 8 articles being published in 2016 and a subsequent increase to 23 articles in 2017. In 2018, a total of 19 publications were recorded, but in 2019, there have already been 28 publications, thereby reinforcing the ongoing rising trajectory observed in publication rates. In the year 2020, there was a notable surge in the number of publications, amounting to a total of 42, representing a substantial rise compared to previous years. The year 2021 witnessed a significant rise in output, shown by the emergence of 116 publications during this period. In the year 2022, there was a substantial surge in the quantity of publications, resulting in a total of 142 scholarly works being generated.



**Source: https://app.dimensions.ai*
Search Criteria: "3D Printing" and "Civil Engineering"
Exported: 19/11/2023

This data is sourced from Dimensions at www.dimensions.ai.

Fig. 2 Publications based on the keywords "3D Printing" and "Civil Engineering" 2015 to 2023 till 19th November 2023 data provided by Dimensions AI [45]

The observed substantial rise in publishing rates serves as evidence of the ever-evolving nature of scientific and informational production. Despite seeing a decline compared to the preceding year, the quantity of publications in 2023 remained commendable, amounting to 121. Although there were minor variations in subsequent years, the data spanning from 2015 to 2022 indicates a predominantly positive trajectory in the generation of academic and instructive content. This demonstrates the dynamic and progressive nature of the publishing industry throughout this particular era.

4. Techniques and Tools in 3D Printing

Three-Dimensional Printing, or 3D Printing, is the creation of physical objects from a digital model using a variety of methods and materials. This includes things like enormous automobiles, cities, and costly jewels. The field makes extensive use of fused deposition modelling, binder jetting, selective laser sintering, and digital light processing. Fused Deposition Modelling (FDM) thermoplastic filaments are cheap and widely available. Fused deposition modelling is a cheap and simple additive manufacturing method.

FDM is easier than Stereolithography (SLA) and Digital Light Processing (DLP), which solidifies resin to generate precise 3D models. Furan resin, quartz dust, and binder jetting are used to 3D Print rocks. These printed samples are roasted at high temperatures, and phenolic resin is penetrated to improve mechanical properties. Further microscopic and mechanical testing reveals that the enhanced 3D Printed specimens accurately depict rocks' robustness and fragility. Micropores and particle adhesion improve mechanical properties. Microscopic micro-pore formations show fractal dimensions related to pore area. Subsurface engineering may benefit from understanding the mechanical properties of comparable materials (Zhang et al. 2023).

3D concrete printing is transforming the building industry by piling Concrete using specialised printers that computer models direct. In order to make the concrete mixture strong and flexible enough to construct walls, columns, and structures, CAD software modifies the mixture. This technology provides for flexible design of delicate architectural details, speedy construction, and reduced labour and material waste. Despite material formulation and regulatory challenges, 3D concrete printing offers sustainable, adaptive, and cost-effective construction options.

5. Building Infrastructure with 3D-Printed Components

The European XFEL facility's quick prototyping of liquid sample delivery systems is covered in the study article. Two-photon polymerization is used to enhance repeatable and high-throughput microfluidic sample delivery devices quickly. 3D Printed devices can be used for the investigation of Single-Particle Imaging (SPI) and time-resolved Serial Femtosecond Crystallography (SFX).

An overview of the methods utilized in XFEL research to deliver liquid samples and to compare droplet PIV and jet explosion procedures can be found in this study (Vakili et al. 2022). This study examines the application of Three-

Dimensional (3D) Printing technology in constructing walls that can potentially serve as partitions within residential structures. Utilizing parametric programming, BIM, and prototypes, a modular reinforced concrete framework and 3D-printed walls were implemented. The study's primary conclusion is that a variety of residential arrangement options can be achieved by combining 3D-printed walls with a reinforced concrete structure. 3D Printing technology integration may find its way into the mass house manufacturing sector (García-Alvarado, Moroni-Orellana and Banda, 2022). This examination looks into the advantages and efficiencies associated with using 3D Printing technology within the framework of a case study involving the military.

The main focus of this presentation is on the use of 3D Printing technology to produce concrete dragon teeth and other strange items. This research critically examines the advantages and disadvantages associated with the application of 3D-printed construction technology in areas regarded as frontier or outposts. Using a commercially available proprietary mortar combination and a gantry-style 3D Printer, the constructions are created as a single unit. In conclusion, 3D-printed construction is faster, safer, and more efficient than conventional building methods. Using pre-mixed materials increases costs and degrades the environment (Jagoda et al. 2020). This article examines the potential implications of 3D Printing technology within the building sector. The utilisation of 3D Printing technology enables the fabrication of structures characterised by complicated geometry and customised interior design.

The present study utilised a mixed-methods approach, incorporating quantitative research methods through the application of scientometric methodologies, as well as qualitative research methods, to analyse the current state of technological research. Additionally, non-technical topics and trends were also examined. Simultaneous execution of two distinct research methodologies was undertaken (Ning et al. 2021). This study paper aims to analyze and evaluate the advantages and disadvantages associated with the utilization of three-dimensional printing technology in the context of construction projects. Five notable advantages associated with the use of 3D Printing technology have been found in this study. In addition, a total of eleven obstacles have been found and categorized into four distinct groups (Romdhane, 2020). The present paper delves into the concept of a portable 3D Printer designed for construction applications. The analysis that was supplied captures the situation as it is right now.

The use of Three-Dimensional Printing is becoming more and more common in a number of industries. It is now appropriate for the building industry to use 3D Printing (Demyanov and Popov, 2019). In addition to showcasing several examples of 3D Printed structures, this article delves into the potential uses of these technological developments in the building industry. Both traditional construction methods and the use of 3D Printing technology for creating concrete buildings are employed. In summary, the utilization of 3D Printing technology within the building industry in Jordan is highly recommended. This paper elucidates the beneficial impacts of 3D Printing on various domains, including the economy, environment, structure, and design (Allouzi, Azhari and Allouzi, 2020).

6. 3D Printing's Potential Use in the Field of Civil Engineering

Civil engineers like 3D Printing because it addresses problems and could change the industry. Using 3D Printing to build could change the game. Civil Engineering covers building, material science, structural design, and product creation. 3D Printing allows the creation of complicated architectural features, structural parts, and skyscrapers with accurate material deposition on each layer. This innovation simplifies the building process, expands design flexibility, lessens material waste, and encourages environmentally friendly design. Civil Engineering 3D Printing enables on-site building and problem-solving in inaccessible or challenging construction sites. Research in additive manufacturing has advanced Civil Engineering. This gadget could change construction. This research investigates using sophisticated geopolymer materials from construction and demolition waste to manufacture 3D-printed buildings.

This study evaluates material constructability using numerical modelling and other modelling and simulation methods. After studying the fresh-state properties of geopolymer-based materials, spherical shapes were printed using 3DP under controlled conditions. The analysis suggests that different building heights can handle different diameters. Comparing the computational and experimental data sets shows that the numerical model accurately projects early failure in 3D Printed structures. This study suggests that numerical modelling can be used to determine if a structure can be built and if it will fail during construction before 3D Printing (Khan et al. 2023). This study investigates the potential trajectory of architectural innovation by analysing the current proliferation of 3D Concrete Printing (3DCP) technology. This highlights the lack of uniform development approaches and building procedures resulting from the use of independently developed technology across multiple universities.

This study examines 42 architectural works that were created over five years using 3D Concrete Printing (3DCP) and quantitative analysis. The main aim of the study is to examine how production methods impact the final structural shapes. The Workspace Index, Geometric Complexity Index, and Tectonic Prospect Index are used to evaluate architectural form. Three themes that the investigation found are expected to have an impact on future forms of 3DCP building:

intelligent construction, algorithmic structure, and transportable equipment (Huang, Xu and Li, 2022).

One common additive manufacturing technique used for quick processing is Fused Filament Fabrication (FFF 3D Printing). The ability to construct complex and customised components is a major benefit of three-dimensional printing. The 3D Printing method and feedstock applications have advanced as a result of recent research. In order to create a sandwich composite with a syntactic foam core, the current study used the skin-core-skin printing approach. High-Density Polyethene (HDPE) and Ground Granulated Blast Furnace Slag (GFBFS) combinations with a volume composition ranging from 20% to 60% are extruded to generate filaments. FFF printers frequently use HDPE and HDPE/GDBFS filaments to create the syntactic foam core and the sandwich structure's outer layer (Bonthu et al. 2020).

CNF nanocomposite derivatives of biomed clear, a medical-grade UV-cured resin for SLA 3D Printing, were investigated for mechanical performance, surface morphology, temperature, and dynamic thermomechanical properties. For SLA 3D Printing, use biomed clear. Even at 0.5 wt% CNF, mechanical characteristics improved. Biomed Clear CNF with 1% filler functioned mechanically. Medical-grade UV-cured resin is utilised in SLA 3D Printing. Nanocomposite biomed clear/CNFs may improve biomedical mechanical performance, according to this study. Manufacturing nanocomposite materials is cheaper than matrix materials. Although none of the low and high-loading materials requires specific equipment, they cost 1.15 and 4.33 percent more than filler. Industrial use demands low upfront expenditures, say experts. Processability problems hampered thermal behaviour modification. Research is needed to optimise the method and uncover pharmacological or mechanical factors (Vidakis et al. 2022).

Current design-to-concrete 3D-printing fabrication techniques allow for the customization of forms for compression-dominated concrete arches and vaults. However, their applications are restricted by the high facility requirements, such as a robotic arm and a reconfigurable print bed necessary to fabricate overhanging geometries. As a result, it is critical to offer 3D Printers a design-to-fabrication process that does not require any specialised tools. This study introduces a technique for fabricating a more sizable three-dimensional arch structure from concrete blocks by utilising customizable prismatic shapes and a standard gantry-based three-dimensional printer equipped with a flat print platform. The efficacy of this method was validated through laboratory prototyping. This technology minimises 3D Printing infrastructure, making it suitable for building unique compression-dominated structures.

As new design methodologies are developed, this design-to-fabrication technique can accommodate compression-dominated structures with more complex geometries (Lin et al. 2022). The study evaluated the inverted stability of a functioning High-Speed Rail (HSR) tunnel in an aqueous stratum, taking environmental and design considerations into account. 3D Printing scale models visualised the intricate tunnel design. According to measurements, when the Effective Water Pressure (EWP) at the tunnel's bottom is very high, the inverted structure is lifted, leading to kinks in the track in water-rich regions. Tunnels often experience invert abnormalities due to TDS and inadequate drainage, as well as excessive EWP. Blockages in the drainage system cause EWP to rise, which affects the stability of the TDS tunnel invert. In severe circumstances, Open Drainage Systems (ODS) reduce EWP and stabilise inversions. ODS demonstrated in field applications how 3D Printing in model tests resembles the behaviour of an operational tunnel (Li et al. 2022).

7. Extensive Case Analysis from a Historical Perspective

Historically, the process of production has predominantly relied on subtractive techniques. Initially, the practice of machining encompassed subtractive methodologies such as filing, turning, milling, and grinding in order to fabricate precise geometries. The development of materials and hardware specifically designed for use in the early morning hours occurred around the 1980s. The technique of stereolithography was first developed by Chuck Hull of 3D Systems Corporation in 1984. The process employs Ultraviolet (UV) lasers for the purpose of curing photopolymers in a sequential manner, facilitating layer-by-layer assembly. According to Hull, the term "system for generating three-dimensional objects by creating a cross-section pattern of the object to be formed" is used to describe this particular method.

Additionally, the individual in question developed the STL file format, which is widely employed in 3D Printing software. Furthermore, they contributed to the creation of digital slicing and infill techniques, which have extensive applications in other operations (Prakash, 2013). As new technologies emerge, companies are reinvesting in their production infrastructures. Additive manufacturing and 3D Printing have advanced in recent years. Compared to traditional production processes, 3D Printing allows for more complex designs. Businesses in a changing industry must undergo transformational processes to succeed in today's competitive market (Kaya et al. no date).

In order to build the Parque de Castilla Footbridge in Madrid, material and process research was first carried out in a laboratory setting and subsequently applied in a manufacturing context in 2016. The footbridge connects Parque de Castilla and two more nearby parks. In this work, a reduced-size particle bed printer was used to create and assess a composite material made of fiber-reinforced cement. The main goal was to look into how the density and mechanical characteristics of the composite were affected by the printing process as well as the material composition. After being expanded to include a full-scale particle bed printer, the technology experienced a number of technical improvements intended to improve the footbridge segments' quality and control. The findings of the study suggest that technology scaling has resulted in changes related to processes. These differences could potentially impact the way in which people utilize technology (de la Fuente et al. 2022). Plastic failure and elastic buckling in 3D-printed concrete walls are the focus of this four-experiment study.

It investigates topics such as geometric faults, concrete drying times, and printing a complex picnic table. The validity of Suiker's parametric 3D Printing model is established by its concordance with experimental data. Make use of the model's built-in design tools, such as the supplied formulae and graphs, to fortify your 3D-printed masterpieces. Help determine optimal printing conditions, such as printing rate, geometry, and material usage (Suiker et al. 2020).

8. Market Shifts and Emerging Technologies

Among the many advantages of 3D Concrete Printing are waste reduction, increased building speed, and creative possibilities (3DCP). This article highlights the significance of concrete combinations and factors, as well as contemporary advancements in materials, applications, technology, and approaches. Waste materials improve rheology, but improper application might reduce initial strength.

Sand reuse reduces the quality of the final product. We classify existing large-scale 3DCP technologies and stress the need to use the best printing materials to enhance the economic and environmental results of waste management (Tu et al. 2023). This study employs virtual uniaxial compression testing to contrast the advantages of two distinct methodologies. Deformed forms and non-equilibrium forces influence peak load and fissure analysis for fracture analysis, as demonstrated by the numerical results. Next, the incremental technique is used to assess the lattice model for 3DCP constructability.

The forecasts are compared with past numerical results using the load-unload approach. With improved quantitative agreement, incremental lattice models predict critical printing height and faithfully replicate failure scenarios. Based on numerical simulations, buildability is quantified by the incremental approach, which takes into consideration non-equilibrium pressures resulting from deformed printing geometry and localized damage (Chang et al. 2022).

The proposed system uses an innovative yet straightforward way to print documents consistently. Testing with cement-based materials shows that the extruder works as expected. Repeated testing helped us optimize printing and material parameters for long-lasting products. Extrusion techniques and enhanced cement material qualities kept 3D-printed products in shape (Albar et al. 2020).

9. New Discoveries and Ground-Breaking Ideas

3D Printing lets people change food taste, smell, and appearance. Qualified operators and trial-and-error optimization delay consumer uptake of 3D-printed food. Digital image processing helps identify and fix 3D Printing flaws. Automation of printing accuracy testing uses layer-wise picture analysis. Printing errors can be found by comparing over-extrusion and underextrusion to the digital blueprint. Online polling compares quantitative difficulties and human judgements to evaluate printing efficiency and quality. Surveys and computerized image analysis revealed leakage and over-extrusion. Despite sensitive digital equipment, survey participants overlooked negligent under-extrusion printing. Personalized digital evaluation can predict and prevent printing errors. Individualized 3D food processing is more precise and effective with digital monitoring (Ma et al. 2023).

In order to evaluate the success and quality of 3D food printing, online polls, questionnaires, and computerized picture analysis are used. Participants in the survey failed to detect casual under-extrusion despite the use of sensitive digital equipment, while leakage and over-extrusion were identified. The previous paragraph suggested a focused digital inspection to foresee and prevent printing problems. Digital monitoring improves accuracy and efficiency in the creation of customized, three-dimensional food products (Alami et al. 2023). The study finds that slag inclusion enhances metakaolin-based geopolymer concrete for 3D Printing. Slag, sodium hydroxide, and sodium trisilicate are used as mix factors in studies on efflorescence, fresh and hardened features, buildability models, and microstructural reaction products.

The outcomes demonstrated increased constructability, decreased efflorescence and calcite production, and improved durability. SEM-EDS analysis was used to identify the phases of quartz, muscovite, and calcite in cured concrete. The findings show that adding slag to concrete enhances its printing quality, durability, and setting time. The preparation of metakaolin for 3D Printable geopolymer concrete is also discussed (Jaji, van Zijl and Babafemi, 2023). This study proposes to employ 3D Concrete Printing (3DCP) to build a house in the rural Chinese town of Wujiazhuang in order to address the worldwide workforce shortage in the construction industry. Research findings from a variety of academic disciplines have an impact on design, materials, and construction techniques. The workflow removes or reduces manual tasks, saving 62.4% of labour. On-site building time decreases by 24.5% as 3D Printing technology rises from 18.3% to 76.5%.

This technique maximizes construction automation by showing 3DCP's capabilities in full-scale architectural projects and reducing human labour (Xu et al. 2022). Extensive study into cellular metamaterials in nature has sparked innovation worldwide; however, most of these breakthroughs are limited to single materials and applications. Through the use of Additive Manufacturing (AM), complex, multi-material designs that have improved mechanical qualities, usefulness, and environmental adaptability can be produced. Many studies on multi-material additive manufacturing have been carried out recently (Nazir et al. 2023).

10. Discussion

The development of 3D Printing has only had a significant effect on the field of Civil Engineering. Although its original use was as a prototype, technical developments have made it possible to fabricate complex structures, such as unique concrete formwork and accurate scale models of skyscrapers. In the construction sector, adaptability and enhanced efficiency are just two possible advantages. The application of 3D Printing in Civil Engineering is a rapidly growing industry that is attracting a lot of attention and funding. Printing entire buildings and bridges challenges norms while delivering cheaper, greener construction. Future practices are expected to change significantly as a result of this integration, which promises to redefine infrastructure construction through inventiveness and efficiency.

The discourse highlights the significant influence that the advancement of 3D Printing has on the field of Civil Engineering. The evolution of this equipment from a prototyping tool to one capable of fulfilling complex structural demands has brought about significant changes in traditional construction procedures. Technology plays a pivotal role in facilitating adaptation and efficiency, which are fundamental pillars in the process of reinventing infrastructure construction. Moreover, the increased interest and investment in this area point to promising developments in the future. Technology that allows for the 3-D printing of complete structures, like buildings and bridges, is poised to cause a paradigm shift in the construction sector that might lead to more cost-effective and environmentally friendly building practices. Ultimately, this integration reflects an exciting future where innovation transforms the landscape of Civil Engineering practices towards greater efficiency and creativity.

Upon careful consideration of the factors mentioned above, it becomes evident that this fusion of disciplines serves as a harbinger of a promising future as advancements in technology and creativity reshape the landscape of Civil Engineering practices, resulting in enhanced efficiency and ingenuity.

11. Conclusion

The incorporation of 3D Printing technology in various sectors, including Civil Engineering, represents a significant shift in the prevailing paradigm. Since its inception as a prototyping tool, its capabilities have seen significant expansion, encompassing cutting-edge architectural design and intricate structural building. The potential of this technology to radically alter traditional building practices, along with rising investment and market interest, is fueling the birth of creative ideas like printing entire structures.

These innovative ideas present a departure from conventional wisdom and present opportunities for cost-effective and environmentally sustainable infrastructure solutions. The pervasive implementation of 3D Printing signifies the commencement of a novel epoch in which the progress of technology will prompt a reassessment and enhancement of methodologies employed in infrastructure development. The forthcoming built environment will be distinguished by its emphasis on ecological sustainability, innovative design, and optimal resource utilization.

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