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Applications and Advancements of 3D Printing in Construction

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ABSTRACT

Recent years have seen tremendous developments in the building business, with one of the most revolutionary technologies being 3D printing (3DP). Additive manufacturing, or 3DP, has emerged as a significant advancement in several industries, including construction. This review attempts to provide a thorough grasp of the current and future condition of 3DP in the construction sector by reviewing a large number of research, case studies, and industry reports. This study offers a thorough analysis of 3DP in the construction industry, examining the uses, difficulties, and potential of the technology. It provides an overview of several 3DP construction methods, identifies the required tools, and includes information on printer kinds and materials. The paper discusses the advantages of 3DP in construction, such as reduced material waste, increased design freedom, and faster building schedules. The limitations and drawbacks of 3DP in the construction sector are also covered, along with issues with primary costs, regulations, and quality control. Examples of uses for 3DP construction prototypes throughout the world are presented. There is a discussion of the many applications of 3DP in buildings, ranging from large-scale structures to small-scale prototypes. The study's conclusion outlines probable future advancements and 3DP technological breakthroughs that could drastically alter the construction industry.

تطبيقات وتطورات الطباعة ثلاثية الأبعاد في البناء

صالحين العود

قسم الهندسة المدنية، جامعة المرقب، كلية الهندسة القره بوللي، لقره بوللي، ليبيا

الملخص

شهدت السنوات الأخيرة تطورات هائلة في مجال البناء، حيث تعد الطباعة ثلاثية الأبعاد واحدة من أكثر التقنيات إثارةً. وقد ظهرت الطباعة ثلاثية الأبعاد كتقدم كبير في العديد من الصناعات، بما في ذلك البناء. تحاول هذه المراجعة توفير فهم شامل للحالة الحالية والمستقبلية للطباعة ثلاثية الأبعاد في قطاع البناء من خلال مراجعة عدد كبير من الأبحاث ودراسات الحالة وتقارير الصناعة. تقدم هذه الدراسة تحليلاً شاملاً للطباعة ثلاثية الأبعاد في صناعة البناء، وتبحث في استخدامات وصعوبات وإمكانات التكنولوجيا. كما تقدم نظرة عامة على العديد من طرق البناء بالطباعة ثلاثية الأبعاد، وتحدد الأدوات المطلوبة، وتتضمن معلومات حول أنواع الطابعات والمواد. تناقش الورقة مزايا الطباعة ثلاثية الأبعاد في البناء، مثل تقليل هدر المواد، وزيادة حرية التصميم، وجدولة البناء الأسرع. كما تم تغطية القيود والعيوب المتعلقة بتقنية التصوير ثلاثي الأبعاد في قطاع البناء، إلى جانب القضايا المتعلقة بالتكاليف الأولية واللوائح ومراقبة الجودة. كما تم تقديم أمثلة لاستخدامات نماذج البناء ثلاثية الأبعاد في جميع أنحاء العالم. وهناك مناقشة للعديد من تطبيقات التصوير ثلاثي الأبعاد في المباني، بدءًا من الهياكل الكبيرة الحجم إلى النماذج الأولية الصغيرة الحجم. ويحدد استنتاج الدراسة التطورات المستقبلية المحتملة والاختراقات التكنولوجية في مجال التصوير ثلاثي الأبعاد التي قد تغير صناعة البناء بشكل جذري.

الكلمات المفتاحية:
الطباعة ثلاثية الأبعاد للمباني
صناعة البناء.
تقنية الطباعة ثلاثية الأبعاد
تطبيقات الطباعة ثلاثية الأبعاد.

1. Introduction

Sustainability in the built environment has received a lot of attention in recent decades. Researchers and experts attempted to develop simpler and less expensive construction technologies. Over the last few decades, pre-cast or pre-fabrication buildings have largely replaced traditional on-site mixing and casting of concrete in some developed and newly industrialized countries. Greater automation in

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the construction industry, on the other hand, can significantly reduce labour and construction time, increase quality, and lessen environmental impacts. In this context, 3DP was originally introduced as a method of rapid prototyping in 1986 [1]. In the 2000s, researchers and engineers used three-dimensional printers (3DP) to automate construction. 3DP, also known as additive manufacturing (AM), is a method that creates 3D objects from digital files layer by layer. Large-scale structure construction utilizing additive manufacturing processes is made possible by 3DP in construction, sometimes referred to as contour crafting or 3D construction printing (3DCP).

There are various ways available today, but the core premise of AM, in which material is added layer by layer [2], remains the same. Despite their prevalence in a variety of industries, their usage in structures has recently gotten a lot of attention.

Those interested in 3DP have expressed an interest in using this technology to create homes and other structures in order to find more efficient and cost-effective construction methods [3, 4, 5] while minimizing environmental impact [4, 6, 5]. However, the advent of 3DP technology has created new opportunities and has the potential to transform the construction industry.

The importance of 3DP in building stems from its potential to handle various industrial difficulties. For starters, it improves efficiency and productivity. In addition, 3DP in the construction industry has the potential to reduce material waste [7, 8, 9]. Because of the precision of 3DP, accurate material usage is possible, reducing excess waste materials often associated with traditional construction processes. By lowering the environmental effect of construction projects, this can contribute to cost savings and enhanced sustainability. Another important feature is the design freedom and intricacy that 3DP provides. Traditional construction processes can have design limits, especially when it comes to complicated geometries. Complex architectural designs and customized building components can be easily realized with 3DP, allowing for increased flexibility and creativity in the construction process. Furthermore, 3DP in construction has potential for environmentally friendly and sustainable building processes. 3DP can help to make the building sector greener and more sustainable by using environmentally friendly materials, optimizing material usage, and lowering energy consumption.

The goal of this review article is to provide a thorough overview of the uses, benefits, obstacles, recent advances, and future prospects of 3DP in building. The review attempts to offer a comprehensive picture of the current state of 3DP in construction and its prospective impact on the industry by reviewing a wide range of studies, case studies, and industry reports.

2. 3DP Techniques in Construction

Several concrete-based printing processes are currently being utilized or investigated. Each technique uses different materials and fabrication processes and thus each has different potential. According to the materials used and the principle of combining materials, Karslioğlu at el. (2022) [3] divided the 3D manufacturing process into subclasses such as SLA (Stereolithography), SLS (Selective Laser Sintering), FDM (Fused Deposition Modelling), DLP (Digital Light Processing), EBM (Electron Beam Melting), and LOM (Laminated Object Manufacturing). Toiba and Ajaz (2023) [4] have presented an overview of six different 3DP processes, namely Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), Powder Bed Fusion (PBF), Material Jetting, and Binder Jetting. According to Goole and Amighi [10], there are two methods of extrusion-based 3DP: Fused Deposition Modeling (FDM) and Pressure-Assisted Microsyringe (PAM). According to Tay et al.'s review article [11], the rapid development of large-scale 3D concrete printing technology is divided into two techniques: (1) binder jetting and (2) material deposition method (MDM). The main idea behind both of these strategies is to construct any complicated structure by layering little amounts of material on top of one another. In a production scenario, typical construction is subtractive, whereas 3DP is additive manufacturing (AM). AM employs a variety of techniques, as illustrated in Fig. 1 [4], which depicts the most often used AM techniques in each process. In general, AM technology in building and construction is classified into four categories: (1) extrusion, (2) powder-based procedures, (3) photopolymer-based systems, and (4) solid sheets.

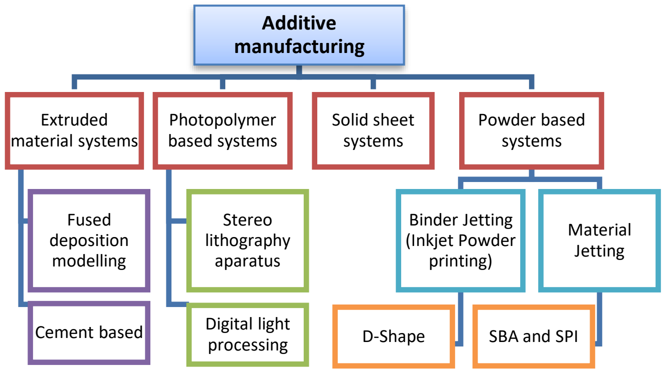

Fig. 1: The classification of additive manufacturing.

1) Extrusion Based System 3DP:

Extrusion-based system 3DP, also known as Fused Filament Fabrication (FFF), is a common 3DP technology. Extrusion is the most common method of Digital Concreting, and it is gaining popularity among many construction companies [12, 13, 14]. Extrusion printing is commonly referred to as nozzle-based deposition technology. Fig. 2 shows the schematic of the fused system of this technique. This technique involves depositing a printable material, typically a mixture of cement, fibers, and additives, layer by layer, with an extrusion nozzle. The material hardens quickly after deposition, allowing for the construction of walls, floors, and other structural features. This theoretical framework is based on the comparison of the vertical stress operating on the first deposited layer with the crucial stress corresponding to plastic deformation and linked to the material yield stress [15]. It is important to point out that bonding strength reduces with increasing time between layers [16].

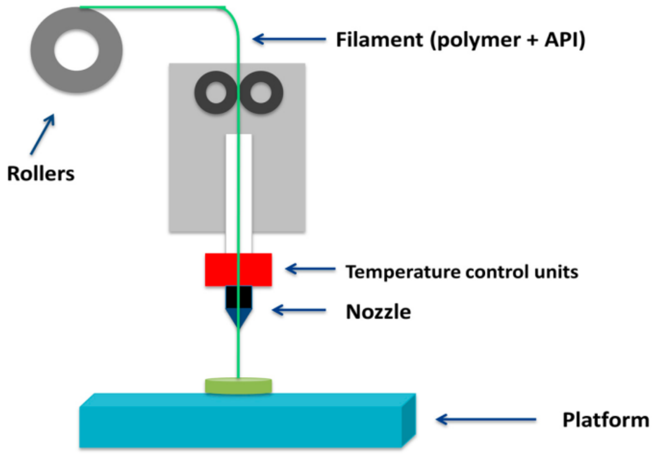

Fig. 2: Schematic of extrusion 3DP - Fused deposition modelling (FDM) Printing system [18]

However, additive manufacturing extrusion can be turned into a very efficient and durable construction process on an industrial scale. To successfully achieve this goal and optimize the procedure, two fundamental constraints must be overcome [17]: First, the bonding between the layers is a vulnerability in the printed structure. Another constraint is to monitor the material's hardening over time: the material must be hard enough to support the weight of subsequent deposited layers. This constraint may result in a longer production time.

2) Photopolymer based systems

i. *Digital Light Processing (DLP):* One of the most recent 3DP methods is Digital Light Processing (DLP). Its central concept is the digital light projection of things via micro-mirrors. Fig. 3 illustrates the Schematic of the DLP. The method can be used to replace conventional high-cost 3DP procedures. The technique is most commonly utilized in prototyping, which is typically done by engineers and designers. DLP 3DP make it easy to create a variety of models. However, the resolution of DLP prints might vary depending on the pixel size of the projector used. DLP is appropriate for applications that require speed without compromising on detail.

ii. *Stereolithography (SLA):* SLA printers is a type of 3DP method in which liquid resins are cured into solid objects layer by layer using a laser. The Schematic of this system is shown in Fig. 4. While SLA printers are mostly employed in the automotive, aerospace, and healthcare industries, there have been recent advances in applying SLA technology in the construction business.

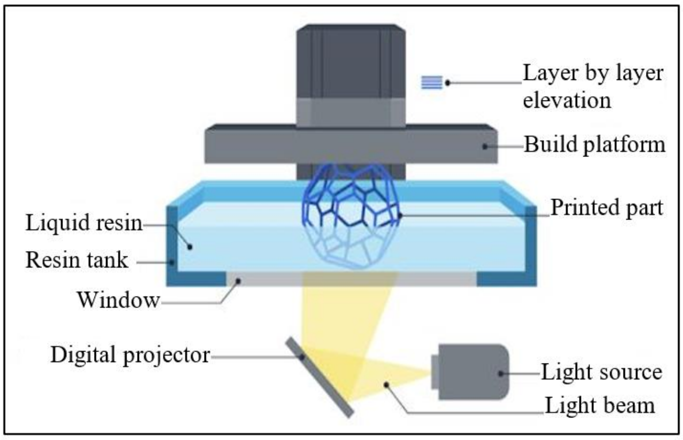

Fig. 3: Schematic the Photopolymer based systems - DLP 3DP [19]

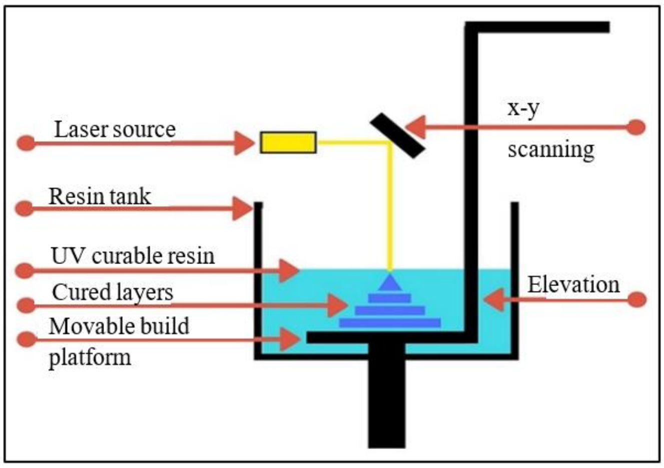

Fig. 4: Photopolymer based system - Schematic of the SLA 3DP [19]

In construction, SLA are typically large-scale machines capable of printing huge structures such as walls or complete buildings. The printer employs a gantry system to move the print head along the X, Y, and Z axes, and the printing material is a vat of liquid resin. The liquid resin is selectively cured by exposing it to a laser, resulting in a solid layer that clings to the prior layers.

3) Powder Based System 3DP

In this technique, a binder liquid is jetting through a nozzle to glue powders together to form a three-dimensional entity. a small coating of powder, often made of concrete or a related substance, is selectively cemented using a binding agent or a chemical reaction. The bottom layer is 3 mm thick, a thin coating of new powder of roughly 0.1 mm is added, and the bed surface is smoothed with the roller [4]. When a layer is finished, the binder feeder feeds the binder solution into the print head and forces it out the nozzle. In this line, Xia et al. [20] have described a new process for creating geopolymer materials for powder-based 3D printers. However, powder-based printing is best suited for small-scale building components, limiting the technology's use to large-scale construction. Powder-based printing is ideal for creating detailed designs with complex geometry. The schematic of the powder-based 3DP is shown in Fig. 5. Non-extrusion 3DP technology is ideal for small-scale components such as panels, permanent formworks, and internal structures, which may subsequently be linked on-site [6]. Heat treatment or infiltration can improve the strength and durability. The non-extrusion procedure is an alternative to extrusion used to create prefabricated concrete pieces.

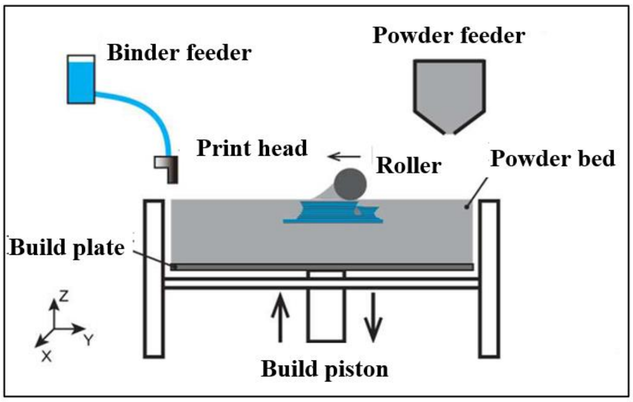

Fig. 5: Schematic of the powder-based 3DP method [21]

3. Materials of 3DP in construction

To meet the unique needs of each project, the construction sector has used a variety of 3DP materials. Here are some of the most widely used materials in construction 3DP:

1) Concrete:

Concrete is one of the key materials used in 3DP. In 3D building printing, it is frequently the main material utilized. It is typically made up of cement, water, additives, and aggregates like sand and gravel. Concrete that is suitable for 3DP has been properly blended with additives or special binders to enhance its flowability and setting properties. It is designed to be extruded by the 3D printer's nozzle or deposition system with the proper viscosity, flowability, and setting time. After curing, the material should also reach a certain level of strength and durability. Benefits: Superior structural qualities of 3DP concrete make it appropriate for a variety of building uses.

In order to increase its strength and resistance to cracking, this concrete occasionally contains extra fibers, also known as “fiber-reinforced concrete” such as steel or synthetic fibers. Better tensile strength and ductility are provided by the fiber inclusion, which qualifies it for use in structural parts that must resist bending or tensile stresses. The benefits of fiber-reinforced concrete increase the 3D-printed constructions' overall robustness and durability, making them more resistant to damage and cracking.

2) Geopolymer Concrete

Geopolymer concrete is made of inorganic polymers and can be used as an alternative to typical Portland cement-based concrete. Its binders are alkali-activated materials such as fly ash or slag. It is well-known for its high mechanical strength and resistance to fire and chemicals. Geopolymer concrete is noted for its low carbon footprint and high fire resistance. It can be utilized as an environmentally friendly alternative in 3D construction printing. Geopolymer concrete has benefits and can be a sustainable material for 3D-printed constructions. Geopolymer-based materials are continuously being investigated and developed for 3DP uses in buildings.

For usage in powder-based 3D printers, Xia et al. (2019) [22] initially created geopolymer binder materials using solely slag combinations. As a result of their research, they later expanded to include mixtures of fly ash and slag. They looked at how much fly ash was added to the geopolymer mixture and how that affected its compressive strength and 3D printability. The study's findings revealed that while the amount of fly ash added to the combination decreased its wettability and compressive strength, it had no effect on the mixture's settleability. It was found that samples with 50% fly ash and 50% slag made the best mixture. Panda et al. (2018) [23] examined the effects of varying time intervals, ranging from one to twenty minutes, on the bonding strength of geopolymer mortar samples that were 3D printed and had two layers of extruded filament. For time intervals longer than one minute, a decrease in strength was noted. It was discovered that the strength decline is amplified by longer time intervals. This behavior was ascribed to a rise in the geopolymer's structuration rate, which resulted in inadequate interlayer bonding and a reduction in the strength of the tensile bond.

3) Cementitious materials:

Apart from traditional concrete, other cementitious materials are also used in 3DP. These materials may include cement-based composites, fiber-reinforced concrete, or alternative cementitious binders.

Cementitious materials that are appropriate for 3DP often need to be fluid, buildable, have a sufficient setting time, have dimensional stability, and have a sufficient extrusion capacity (moldable and extrudable material). These materials provide improved flexibility, durability, or certain qualities needed for particular uses. a few researchers and industries have successfully printed various cementitious materials using Ordinary Portland Cement (OPC) as a key binder in their mix compositions [24]. Several tests on the workability, printing durability and accuracy, and printing ease of cementitious printing mixes were conducted by Kazemian et al. (2017) [25]. According to the experiment's findings, adding Nano-clay and silica fume to four different kinds of combinations significantly improved the printing mixtures' stability. Time plays a significant role in cementitious materials because the various stages of the hydration process—also referred to as concrete maturity—achieve varied results over time [26]. In 3DP, surface moisture is lost during the interval between two succeeding layers, which may have an impact on the strength of the bond. Nonetheless, the moisture content of the deposited layers is also significantly influenced by temperature and humidity. Dry cementitious materials usually create a weak zone at the point of intersection, which considerably weakens the bond [26].

In a study by Yang et al. (2020) [27], cementitious materials (3DPC) based on nano-CaCO3 (NC) were tested with four replacement ratios of NC to binder from 1 to 4%. The findings showed that adding 2% of NC showed about 7.2, 39.1, and 22.5% higher compressive strength for the three mixes with NC than that of the control mixture at 7, 28, and 90 days. Kim et al., 2019 [28] conducted an experimental investigation to examine the dimensional stability of cementitious mixes modified with styrene butadiene rubber (SBR) and assess if these mixtures' qualities could be sustained as a 3D additive building material. The study's findings demonstrated that, with the exception of the coefficient of thermal expansion, the drying shrinkage strain and elastic modulus all greatly improved as the SBR/cement ratio increased. Effective microorganisms (EM) were used by Ibrahim et al., 2024 [29] to strengthen the interfacial connections between the layers in LC3 fiber-reinforced printed concrete (FRPC). In order to study interfacial strengthening and decreased anisotropy, an experimental campaign involving three destructive tests (compression, direct tension, and flexure) was carried out on EM-enhanced LC3-FRPC and reference LC3-FRPC. In conclusion, compared to non-EM specimens, the material in the interlayer region of EM-enhanced specimens showed smaller pore sizes and reduced porosity. The average interfacial bond strength values of the tensile and flexural specimens with EM-enhanced strengths were 6.27 MPa and 1.45 MPa, respectively. These values were 33.7% and 26.1% higher, respectively, than those of the specimens without EM.

4) Composite materials

Construction 3DP also uses composite materials, which are mixtures of several materials. For instance, to construct lightweight, durable, and high-performance structures, fibers (e.g. carbon or glass fibers) can be placed in a matrix material (like concrete or polymer). Improved strength-to-weight ratios and application-specific tailoring are provided by composite materials. It's vital to remember that the particular 3DP technology and apparatus utilized can affect the availability and application of materials in construction 3DP. New materials and formulas are being investigated as part of ongoing research and development efforts to enhance the capabilities and uses of 3DP in the construction sector. A study by Lin et al. 2020, [30] demonstrated the mechanical enhancement offered by a novel mortar–polymer laminar composite. Displacement-controlled compression tests were carried out on three different composites. One of these was made with normal mortar, while two had added waste material components: biochar or fly ash. Polymer reinforcement increased the overall ductility of all composites that were cured in air-dry conditions the relevant condition for material printed on-site. These ductility improvements were seen even though the addition of the polymer decreased the overall peak compressive stress in all but one case.

4. Characteristics of 3DP in Construction

As previously noted, 3DP offers many benefits to the building industry, but it also has several drawbacks that can be stated as follows:

1) Advantages

i. *Design Flexibility and Customization:* 3DP gives designers and architects more creative freedom. They might create intricate and complex structures that are difficult or impossible to produce with traditional methods. It makes highly customized and unique building concepts possible.

ii. *Quickened Building Procedures*: By automating and simplifying numerous steps, 3DP can greatly accelerate the construction process. Rapid production of complex components eliminates the need for conventional formwork and lowers the amount of manual labour needed.

iii. *Sustainability:* Through more effective resource use and waste reduction, 3DP helps lessen the negative environmental effects of building. Construction 3DP employs additive manufacturing, which reduces material waste in comparison to subtractive manufacturing techniques. The exact deposition of materials leaves little residue, minimizing its negative effects on the environment and conserving money.

iv. *Enhancing construction safety:* 3DP can lower the risk of accidents and injuries by automating the construction process. This is because additive manufacture of components takes place in controlled conditions, which lowers the risks related to on-site construction activities. By doing this, possible dangers are decreased and worker safety conditions are improved.

v. *Cost savings:* Despite 3DP technology and equipment may require a large initial investment, there is a significant chance of long-term cost savings. Overall cost efficiency in building projects can be achieved by reducing wasteful use of materials, labor expenses, and construction time.

2) Disadvantages

i. *Restricted Material Selection:* There are currently just a few building materials that can be used in 3DP, and they might not be as strong or adaptable as more conventional building materials. The most often utilized materials are a variety of concrete combinations, which could have drawbacks in terms of strength, toughness, and visual appeal. There is continuous research and development being done to increase the variety of printable materials.

ii. *Complexity:* Since 3D printing technology is still in its infancy, it calls for specific knowledge and abilities that the construction sector may not have easy access to. To efficiently operate and maintain the equipment, designers, engineers, and technicians require training. The sector must also produce a workforce with the necessary skills to use 3D printing technology.

iii. *Regulatory and Legal Challenges:* Because 3D printing technology does not yet comply with all building rules and laws, it may encounter regulatory obstacles and compliance problems. These could cause delays or complicate the process of getting permits and approvals. It may not be possible for building laws and regulations to fully account for 3D-printed structures, necessitating the creation of new guidelines and standards.

iv. *Maintenance, Structural Integrity, and Quality Control:* The consistency, robustness, and longevity of printed components must be carefully examined to meet safety standards and long-term performance requirements. This makes it difficult to maintain the 3D-printed construction's structural integrity and quality control. Additionally, buildings may require specific maintenance and repairs that normal buildings do not require due to the unique materials and construction procedures used.

v. *Scalability and Initial Investment Costs*: 3D printing is useful for small-scale projects, but for larger, more intricate constructions, it might not be as feasible or initially affordable. Initial costs can entail large upfront expenditures, which could be prohibitive for projects with tighter budgets or smaller construction companies. It is anticipated that costs will drop as technology develops and becomes more widely used.

5. Examples of 3D printing Applications in the construction industry

As technology advances, it is likely to play a larger role in revolutionizing how buildings and infrastructure are designed and built. The samples below demonstrate the various applications of 3D printing in the construction sector, which range from residential homes and offices to bridges and formwork constructions.

1) Tor Alva or White building.

In April 2024, the technological institute ETH Zurich completed 8 of 32 structural columns that were designed and printed with concrete for the Tor Alva or White building. The design by architects Michael Hansmeyer and Benjamin Dillenburger is 30 meters tall and made up of 32 unique Y-shaped columns, each with a textured detail pattern, as shown in Fig. 6. The Tor Alva will be the world's largest 3D printed structure, located in Mulegns, Switzerland.

Fig. 6: The tallest 3DP structure -Tor Alva- to April 2024 [31]

2) Dubai's smart villa

In December 2023, the government of Dubai launched the first smart 3D printed villa constructed by U+A Architects via COBOD, and launched a project to construct a neighbourhood of 3D-printed villas. The villa is printed using a combination of cement and other construction materials. The mansion, built by U+A Architects, spans 202 m^2 and includes various unusual design aspects, like curving walls and huge windows. Unlike earlier 3D-printed houses, this villa integrates Xiaomi's Mobile X AIOT products, such as smart vacuums, air purifiers, cameras, and other smart home technology. Fig. 7 shows the landscape of the vella. This breakthrough has the potential to completely transform the UAE's smart living scene. The project aims to provide affordable and sustainable housing solutions while showcasing Dubai's commitment to technological innovation.

Fig. 7: The first 3D-printed villa with smart house technologies - Dubai [32]

3) luxury horse barn

In June 2023, Wellington, Florida, USA, Printed Farms used COBOD's BOD2 construction 3D printer to build the world's largest 3D-printed building. The project shown in Fig. 8 was a luxury horse barn and first permitted 3D printed house in Tallahassee. The equestrian facility is 4 meters high and has a total floor size of 939 m^2. The building is impressively 47 meters long and 25 meters wide overall.

Fig. 8: Luxury horse, the world's largest 3DP structure to 2023 [33]

4) The world's tallest 3DP building in Saudi Arabia

In 2022, COBOD and Dar Al Arkan built the world's tallest 3D-printed building. Unveiled in Saudi Arabia is the world's tallest 3D printed building up to date, standing at 9.9 m (Fig. 9). The company and Dar Al Arkan, a Riyadh real estate firm, unveiled what they describe as the world's highest 3D printed structure, which is situated in Saudi Arabia. In this instance, the three-story 3D printed structure is situated in Shams Al Riyadh, a roughly 12-million-square-meter development project. Based on the D.fab solution, which was created by Cemex and COBOD and enables customers to acquire 99% of concrete components locally, the house was constructed using inexpensive local materials to build the concrete. The 345 m^2 residence is divided into two floors: the first has a large hall with many living areas, and three bedrooms, two bathrooms, a living room, and a balcony. The maid's room, laundry room, and multipurpose hall are located on the third story, which is smaller than the other floors and could be referred to as a roof annex in Saudi Arabia.

Fig. 9: The world's tallest 3D-printed building to 2023 [34]

5) Oudezijds Achterburgwal bridge

In 2021, a 12-meter 3DP pedestrian bridge in Amsterdam was unveiled by Joris Laarman and constructed by the Dutch robotics company MX3D. The Oudezijds Achterburgwal bridge in Amsterdam's Red-Light District illustrated in Fig. 10 was built from stainless steel rods using six-axis robotic arms fitted with welding equipment. 4,500 kg of stainless steel were used in the structure, which was craned into place above the canal this year after being 3D printed by robots in a factory over six months. Software for parametric modelling was used to develop its curved S-shaped form and balustrades with perforations resembling lattices.MX3D Bridge, Netherlands: The MX3D Bridge, located in Amsterdam, is the world's first 3D-printed stainless steel pedestrian bridge. The bridge was created using robotic arms equipped with 3D printers, which printed the structure layer by layer. This project demonstrated the potential of 3D printing for creating large-scale metal structures in the construction industry.

Fig. 10: The MX3D Bridge was 3D printed out of stainless steel and is situated in Amsterdam's Red-Light District [35].

6) Gaia Building – TOVA - in Barcelona

In 2020, Spain's first building made with earth and a 3D printer called TOVA was Gaia Building in Barcelona as shown in Fig. 11. The building showcases the use of 3D printing for creating sustainable and energy-efficient structures. It was made using a 3D printing system that extrudes a mixture of cement and other construction materials. The research project of TOVA was developed by a group of students, researchers, and professionals from the 3D Printing Architecture postgraduate program of the Institute for Advanced Architecture of Catalonia (IAAC). It was made in collaboration with WASP using a Crane WASP, and it was finished in a few weeks with 100% local materials and labour, low waste.

Fig. 11: The first structure TOVA in Spain was created by 3DP and Earth [36]

7) Apis Cor firm in Russia

In 2017, the Apis Cor firm 3D printed, as shown in Fig. 12, the first residential house in Russia in one day. An automatic unit of mix and supply and a mobile 3D printer were utilized in the building. The entire structure, including the walls, partitions, and building envelope, was printed on-site using a mobile 3D printer. That was in contrary to custom 3D printing which creates the building parts as separate pieces, in facilities away from the construction site. The project showcased the feasibility of rapid and cost-effective construction using 3D printing technology. They were developed by Apis Cor, particularly for this purpose. Apis Cor's curved-shaped house has an area of 37 m^2. This particular shape was selected rather than others. It was chosen to highlight the magnificent capabilities of the 3D printer that can create any desired building shape. The hard Russian winter that occurred during the creation of the 3D printed house was not conducive to the procedure. The temperature at which the concrete mixture forms in the printer is only more than 5 degrees Celsius, even though the printer itself may operate at as low as -35 degrees Celsius. As a result, a tent was erected to insulate the outside and improve the temperature for the concrete mixture. Up to 70% less money is spent on the new technology than on typical block buildings.

Fig. 12: The first on-site 3D printed house in just 24 hours in Russia by Apis Cor [37]

8) Office of the Future in Dubai

In (2016), Office of the Future, Dubai is the first fully operational 3D-printed structure in the world. The 250 square meter Office of the Future, showed in Figure 13, which opened its doors in 2016, is the first structure designed with full functioning and built to scale [38]. It has meeting rooms, a café, a lounge, and creative working areas. Most essential, though, is that the building's distinctive design makes it extremely sustainable and energy-efficient. Optimized designs for natural light and plenty of shade minimize the need for lighting and air conditioning in the office. Constructed in less than a month using an industrial printer, this amazing structure is a step in the right direction for the building industry.

Fig. 13: The world's first fully functional and permanently occupied '3DP' building (The Office of the Future) [39].

9) World's highest 3D Building in China by WinSun

In 2015, the Chinese WinSun Decoration Design Engineering company unveiled a printed structure with five stories consisting of assembled structural segments (Fig. 14). The structure is built of recycled construction materials. The machine prints enormous parts of buildings (such as wall panels) layer by layer with "ink" made of fiberglass, steel, cement, hardening agents, and recycled construction materials.

These components are then assembled on-site, much like precast concrete, to form the final construction. The enormous custom-built 3D printer cost the corporation approximately $2.3 million and took 12 years to create. It is 6.6 meters tall, 10 meters wide, and approximately 150 meters long. According to the company's, their 3D-printed walls are significantly stronger and more durable than concrete walls while also weighing around 50% lighter.

Fig. 14: The world's highest 3DP structure with five stories consisting of assembled structural elements [40]

6. Conclusion

In conclusion, studies on the uses and developments of 3D printing (3DP) in the building sector have shown that this technology has the potential to completely transform the sector. Enhanced productivity, decreased material waste, and the capacity to produce intricate and personalized designs are just a few advantages that come with 3D printing.

Large-scale printers that can build entire buildings in a fraction of the time and cost of traditional construction methods have also been developed as a result of advances in 3DP technology. These developments have given engineers, architects, and construction firms additional opportunities to design creative, environmentally friendly buildings.

Although 3D printing in building has many benefits, there are obstacles to be addressed. Some drawbacks of this technique are limited material selection, regulatory obstacles, and initial investment expenditures. However, these issues should be resolved when standards change and the industry adjusts. To fully realize the potential of 3DP in building, more study and cooperation amongst stakeholders will be required in the future.

The ways that 3D printing is being applied and developed in the construction business show how this technology has the power to completely change the way that structures are planned and built. Benefits include increased safety, sustainability, cost effectiveness, quicker construction procedures, reduced material waste, and design freedom.

Overall, 3DP's future in the building industry is promising, and technology has the potential to solve the world's housing and infrastructure demands, enable customization, and produce creative and effective building solutions as it develops further.

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