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The State of 3D Concrete Printing: Current Applications and Future Opportunities

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ABSTRACT- 3D printing technology has brought remarkable improvements to manufacturing processes. By converting digital designs into physical objects, it allows for the quick and accurate production of items with intricate geometries. This technology reduces costs while offering enhanced production flexibility. In fields such as jewelry making, medical prosthetics, the food industry, and construction, 3D printers are continuously expanding their applications and evolving with each passing year. In the construction sector, 3D printing has become a key driver of the automation revolution, significantly changing traditional building methods. It offers notable advantages, such as lower costs, faster construction timelines, and improved sustainability. With this technology, construction materials can be directly printed on-site, making it possible to create even highly complex designs with ease. This approach not only minimizes material waste but also enhances energy efficiency. Ranging from prefabricated building components to cost-effective housing projects, 3D printing provides essential solutions, especially in areas requiring rapid construction. Additionally, it allows for greater creative freedom in architectural design, enabling the realization of more innovative and sustainable structures. In short, 3D printing is playing a transformative role in reshaping the construction industry. In conjunction with other automation technologies, it is making construction practices more efficient, economical, and environmentally friendly. This paper examines the advantages and current uses of 3D printing in construction, drawing on findings from recent studies and real-world applications.

KEYWORDS- 3D Concrete Printer, Additive Manufacturing, Construction Technologies

I. INTRODUCTION

3D printing technology stands out as a groundbreaking innovation that has transformed the fields of production and design. First introduced in the 1980s, this technology has gained widespread adoption owing to its capability of transforming digital designs into tangible objects. Also referred to as additive manufacturing, 3D printing involves dividing a three-dimensional model into layers and building it up layer by layer using various materials. Unlike traditional manufacturing techniques, 3D printing can create intricate and complex designs in a single production process, offering significant time and cost savings.

One of the most significant advantages of 3D printing is its ability to produce geometries that are difficult or even impossible to achieve with conventional manufacturing methods. Complex structures, hollow forms, and detailed designs can be easily materialized from digital models. This flexibility is particularly valuable in prototype development and customized product design.

With ongoing technological advancements, the scope of 3D printing applications continues to broaden at a rapid pace. It is revolutionizing industries ranging from manufacturing and healthcare to jewelry design and even food production. In the medical field, for instance, 3D printing has become a critical enabler for the fabrication of bespoke prosthetics and anatomical models. In education, it offers students hands-on and interactive learning experiences, while in art and fashion, it empowers creators to bring innovative designs to life.

The variety of materials available for 3D printing further enhances its appeal. In addition to traditional materials such as plastics, metals, and ceramics, modern 3D printers can now utilize advanced biomaterials and sustainable resources. This versatility positions 3D printing as a promising solution to global challenges such as sustainable manufacturing and environmental conservation.

In recent years, the construction industry has undergone significant transformation driven by technological advancements, with 3D printing emerging as a central force in this change. This innovative technology is gradually replacing conventional construction methods, offering more efficient, cost-effective, and sustainable alternatives. 3D printing enables the direct fabrication of construction materials through advanced printing systems, enabling the seamless execution of intricate architectural designs. This capability provides clear advantages over traditional construction practices.

Today, the integration of 3D printing into construction practices is gaining significant traction, with applications ranging from prefabricated building components to large-scale housing projects. It has also proven to be a valuable solution in regions affected by natural disasters or experiencing rapid urbanization. The rising frequency of natural disasters has intensified the demand for innovative housing solutions, Underscoring the critical role of technologies such as 3D printing.

Moreover, 3D printing Effectively tackles persistent challenges in construction, including labor shortages, material costs, and waste management. It also fosters architectural creativity, enabling the design and construction of more innovative and sustainable buildings. 3D-printed structures deliver notable benefits, particularly in energy efficiency and material optimization, contributing to reduced environmental impact. Additionally, the use of eco-friendly materials and the minimization of waste further enhance the environmental benefits of this technology.

This study seeks to comprehensively analyze the benefits and contemporary applications of 3D printing technology within the construction sector. By examining diverse studies and real-world applications, it highlights how 3D printing revolutionizes conventional construction practices while shaping the industry's future.

A. History

The advent of the first commercial 3D printer can be credited to Chuck Hull in 1980. At the time, Hull was working for a company that used UV technology to produce durable tabletop coatings. Through extensive experimentation, he succeeded in applying layer-by-layer manufacturing by integrating computer-aided designs with UV technology. UV light facilitated the rapid solidification of liquid, acrylic-based materials, enabling swift layer curing. As a result of these efforts, a process known as Stereolithography (SLA) was developed, marking the inception of the first commercially used 3D printer in history [1]. 3D printing technology continues to evolve, finding applications across diverse industries, and specific 3D printing technologies are being developed to suit these various application areas. As outlined in Table 1, ASTM Standard F2792-12a categorizes additive manufacturing methods into the following groups [2] Sheet lamination, direct energy deposition, binder jetting, material jetting, powder bed fusion, vat polymerization, material extrusion.

Table 1: Groups of 3D printing technologies according to ASTM Standard F2792-12a [2]

Process	Description
Sheet Lamination	Joining material sheets to form parts.
Direct Energy Deposition	The fusion of materials by selectively melting them using thermal energy.
Binder Jetting	Binding specific regions of the powder bed with a liquid bonding agent.
Material Jetting	The deposition and curing of material in droplet form.
Powder Bed Fusion	The thermal consolidation of powder within the bed.
Vat Polymerization	Curing through light-activated polymerization.
Material Extrusion	The placement of fluid material through a nozzle or orifice.

Sheet Lamination (laminated object manufacturing) is a prototyping method that allows for the rapid and economical 3D printing of various objects. This method involves layers of adhesive-coated paper, plastic or metal laminates. The adhesive tapes are bonded by applying solvent to the layers. A heated roller then compresses the tapes, creating a stronger bond. Cross sections of the model are laser-cut, creating individual layers. Each layer is then glued together to create the model. This system is used only for prototyping purposes and is not preferred for production and is based on a different principle than other printing methods [3].

Directed Energy Deposition technology is based on melting and combining the material with thermal energy. In Directed Energy Deposition technology, thermal energy is concentrated using an energy source such as a laser and the raw material consisting of metal powders is melted and combined. Although this technology has special capabilities, it has a limited area of use in the additive manufacturing market. For example, functional and superior parts can be produced by printing multiple materials at the same time. The Directed Energy Lamination machine can move in 4-5 axes with a robot arm that directs the print head. Therefore, the production process is not limited to parallel and horizontal layers. This technology also allows for the addition of new material to pre-existing components [4].

Binder Jetting is an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials [2]. Because of the use of liquid binders in the production of geometric models, Binder Jetting can create colorful objects through colored binders. Binder Jetting offers the ability to print diverse materials, including metals, sands, and ceramics, while providing advantages such as lower costs, faster production speeds, and reduced heat-related errors [5].

Material Jetting involves the layer-by-layer deposition of building material onto designated areas using one or more print heads. This process utilizes photopolymer or wax-based materials [4]. This system works with a part similar to an inkjet print head. Sacrificial support materials are automatically produced and deposited with photopolymers to support the overhanging structures. Inkjet 3D printing technology is capable of producing prototypes, lightweight honeycombs, lifestyle wearables, custom anatomical models, and tissue engineering scaffolds [4].

Powder Bed Fusion technology was developed and patented in the mid-1980s by Dr. Carl Deckard and his academic advisor Dr. Joe Beaman at the University of Texas at Austin, under the sponsorship of DARPA [6]. The Powder Bed Fusion process works by penetrating thermal energy into a specific area of a powder bed. The thermal energy melts the powdered material together, which then cools and forms a solid model. Other terms used for this type of layer-by-layer fabrication process include Laser Sintering, Selective Laser Sintering (SLS), Direct Metal Laser Sintering, and Electron Beam Melting. The energy required for melting the powder is provided by either a laser or an electron beam [7].

The concept of 3D printing stemmed from Charles W. Hull's idea of using UV light to harden table coatings. This idea led to the invention of Vat Polymerization (stereolithography), which forms the basis of 3D printing technology. Stereolithography, the first rapid prototyping technology, enables the fast, precise, and repeatable production of computer-aided parts [8]. Stereolithography is capable of producing objects with intricate geometries and exceptional precision It finds applications across various fields, including medicine, automotive, aerospace industries, as well as art and design. In this process, the system is activated by filling a tank with photopolymer resin and positioning a moving platform just below the liquid surface. A computer-controlled system then pours liquid resin layer by layer, based on sliced sections generated by the software. In this way, each layer is added on top of the other; the layers are bonded together thanks to the adhesiveness of the material and hardened by UV light. If there are gaps while the part is being created, support structures are built, and these supports are separated from the part after the process is completed [9].

Material Extrusion method is an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice [10]. Compared to other additive manufacturing processes, the materials and tools used in Material Extrusion are often more affordable and easier to handle. Therefore, the primary advantage of Material Extrusion is the rapid and inexpensive production of standard components or prototypes with different polymeric materials, even in low melting temperature metallic alloys [11].

Towards the end of the 1980s, Chuck Hull patented the Stereolithography method and introduced his machine called SLA-1, which became the first commercial 3D printer. After Chuck Hull's work, Carl Deckard's patented Selective Laser Sintering method and Scott Crump's patented Fused Deposition Modeling method paved the way for commercialization and development in this field. In 1995, sales of 3D printers began. In 1996, Z Corporation developed the first 3D printer capable of producing high-resolution products. In 2007, the first open-source 3D printers, branded as RepRap, were introduced to the market, significantly expanding the opportunities for 3D printer development. In 2008, Object Geometries made progress with the Connex500, which can produce with different materials at the same time. Since 2009, sales of home 3D printers have increased rapidly, thanks to models such as Makerbot and 3D Systems' Cubify [12 Subsequent developments in 3D printers have continued across various regions and industries. In 2011, engineers at the University of Southampton designed the world's first 3D printed airplane, while in 2012, a joint prosthesis was developed with this technology. In 2014, the first 3D printer was used in space, and the following year in 2015, NASA began manufacturing with 3D printers [13]. As Additive Manufacturing technology gained the attention of academia, governments, the healthcare sector, and industry, significant advancements in 3D printer raw materials have resulted from ongoing research. As a result of production with new high-function raw materials, the technology has advanced from design prototypes to mass production of complex products Furthermore, 3D printers are now recognized for their potential in producing biological tissues capable of improving or revitalizing bone, cartilage, and muscle structures. In this context, institutions such as the National Institutes of Health-NIH, Department of Defense-DoD and US Food and Drug Administration-FDA of the United States have allocated funds for medical 3D printer research [14].

In terms of historical progress in the construction sector, the first publication mentioning concrete material and printing systems was published by Joseph Pegna in 1977. This publication focused on the technique of creating a sand and cement mixture, but it was never realized [15]. Practical studies on 3D printing and construction emerged in the early 90s in the US state of California, when Khoshnevis introduced a technology called Contour Crafting, which allowed structures to be built more quickly and effectively with less labor and less manpower [16]. As with Contour Crafting, Concrete Printing is also based on the extrusion of cement mortar in a layer-by-layer process. This printing process can be performed without the use of labor-intensive molds and has the ability to incorporate functional cavities into the structure [17]. The D-shape process, developed by Enrico Dini and patented in 2006, uses layers of powder and adhesive instead of the cement-like paste used in other methods. The system has many advantages over traditional processes. It can use any sand-like material and produces very little waste [18]. In the following process, companies, academic institutions and individuals based on these production methods have benefited from this technology in areas such as construction elements, construction, sustainability and restoration and have carried this technology forward. Developments related to the construction sector are further detailed in the following sections of the review article.

II. APPLICATIONS OF 3D PRINTERS

A. Education

It is possible to use 3D printing technology in the field of education; however, in order for this technology to be used efficiently, the necessary infrastructure must be provided in terms of qualified personnel, technical support, hardware and software access. In some schools, 3D printing technologies are used to create interactive, mechanical and technical lessons. This technology inspires young people and makes the learning process more enjoyable. The following examples can be given for the use of 3D printing technologies in fields such as architecture, art, biology, chemistry, geology, history, mathematics, science and engineering education [19]:

• In biology class, students can create detailed organ models with 3D printers and conduct experiments to explore these models.

• In chemistry class, students can produce physical models of molecules using 3D printers and thus understand their complex structures more easily.

• In mathematics, challenging topics such as area and volume calculations, geometric shapes, functions, and the representation of the Cartesian coordinate system in space can be visualized and simplified using 3D printers.

• Engineering and design students can easily produce prototypes or parts of their projects with 3D printers.

• Architecture students can create 3D models of their projects in a short time.

• Graphic design students can make their designs tangible by producing 3D models of their work with 3D printers.

• Technical high school students can produce spare parts, modified parts or innovative mechanical parts in line with their own interests and projects with 3D printers.

In a study by Ford and Minshall on 3D printers in education, it was found that students achieve better comprehension of subjects such as biological molecules in biology, atomic structure in chemistry, design and sustainability in design, materials and design in engineering, geometry in mathematics, and enzyme-ligand structures in pharmacy when 3D printing technology is used [20].

B. Aviation and Space

3D printing technology offers unprecedented freedom in the design and production of components. In the aerospace industry, 3D printing has the potential to produce lightweight parts and complex, advanced geometries, which can reduce energy requirements and resource use [21]. Furthermore, 3D printing contributes to fuel savings by minimizing material usage in aerospace part production. 3D printing is also extensively utilized for producing spare parts for aerospace components, particularly engines. Engine parts can be easily damaged and need to be replaced regularly; therefore, 3D printing technology is an effective solution for the supply of such spare parts [22]. In the aerospace industry, nickel-based alloys are more preferred due to their tensile strength, oxidation and corrosion resistance, and damage tolerance properties [23]. With 3D printers, not only plastic parts are now produced, but also metal parts have begun to be printed as a result of developments made in recent years. For example, Renishaw company uses materials such as 316L and 17-4PH stainless steel, Al-Si-a0 and Al-Si-12 aluminum alloys, H12 tool steel, titanium CP, Ti6a14V and Ti6A17Nb titanium alloys, cobaltchrome (ASTM75), 718 and 625 incolen and has produced metal parts with these materials [24].

C. Healthcare and Medical

3D printing technology can be utilized to produce 3D skin, for drug and pharmaceutical research, bone and cartilage, replacement tissues, and organs, as well as for cancer research. Additionally, it is used to create models for visualization, education, and communication [25]. In the health sector, 3D printing technologies are extensively utilized for general product development, manufacturing artificial tissues and organs, creating personalized surgical and medical devices, and producing hearing aids and limb prostheses such as arms, legs, and facial parts. Additionally, these technologies are applied in dental and implant procedures within oral and dental healthcare [26]. In Belgium, two patients received a face and jaw transplant produced using a 3D printer. In Turkey, one of the most prominent examples of the use of 3D printers in the health sector is Sabancı University's "3D Tissue and Organ Printing Project". In this project, an aorta tissue sample was produced from living cells using 3D printers. In the future, it is planned to produce tissue and organs using a 3D printer [27].

D. Food

3D printing technology offers new possibilities not only for the aviation sector, but also for the food industry. There is a growing demand for customized foods tailored to specific dietary needs, such as those of athletes, children, pregnant women, and patients. This demand emphasizes reducing unnecessary ingredients while increasing the proportion of healthy components [28]. 3D printers are also used in the food sector in both food packaging and food production. The first instance of a 3D-printed cake was patented by Nanotek Instruments in 2001. In 2009, a food called "Moleculaire" was designed using multiple materials in the Electrolux Design Lab Competition. Philips introduced specially designed layered food cartridges in 2008. In addition, NASA has developed food printers for use in space [29]. In food production, 3D printers can be used to meet food design and personalized food demands [30]. Different processes are applied depending on the materials used in the food to be produced. The shape and decoration of the dishes can be personalized according to the customer's preference or the occasion. Choc Edge introduced the world's first commercial 3D chocolate printer, the Choc Creator. Various nozzles are used to produce melted chocolate in desired patterns and shapes [31].

E. Textile

3D printers are used in the textile sector for two main purposes. The first involves manufacturing entire garments using 3D printing technology. The second is the creation of unique surfaces employing various connection techniques, offering alternatives to traditional woven or knitted textiles [32]. In traditional clothing production, the process of preparing patterns and samples is quite time-consuming. 3D printing technology adds flexibility to fashion and textile materials. In addition, another advantage of clothing production with this technology is that a factory or workshop is not required for production [33]. Nike utilized Selective Laser Sintering (SLS) technology, a form of 3D printing, to produce lightweight plates for its Vapor Laser Talon and Vapor High Agility cleats. As a result of the trials and tests, some problems were detected, and the cleat and plate geometry were redesigned to fix these problems. Nike has managed to reduce the prototyping and final production time from two to three years to six months thanks to 3D printers [34].

F. Automotive

With increasing competition in the automotive sector, brands are making revisions in their designs in order to both reduce costs and renew their production methods. In order to meet the demands brought by these innovations, 3D printer technologies are used. The use of 3D printers in the automotive and spare parts sector offers lower cost and flexible production opportunities. Given that a vehicle comprises over 30,000 individual components, 3D printing allows for the production and testing of sample parts, enabling the identification and elimination of potential errors prior to mass production. In addition, plastic parts with complex geometries such as bumpers, grilles and fenders can be produced with ABS filament using FDM technology with 3D printer technology [13].

III. 3D PRINTERS IN CONSTRUCTION

3D printing technology, which has demonstrated its effectiveness across various industries, continues to evolve and find innovative applications in the construction sector. In the construction sector, 3D printing systems can be broadly categorized into three types: gantry-based systems, delta systems, and robotic arms. There are differences between the working axes and areas of each category. The 3D printing process can be divided into four categories. Model preparation process; this process is the same in all types of 3D printers. The digital model of the structure to be produced is prepared in a way that is compatible with printing. It is exported in the ".stl" (stereolithography) extension used for 3D printers. This extension allows the prepared digital model to be divided into slices on the z-axis. From here, the stl extension file is imported into the program used by the printer and converted into a coding suitable for the printer's settings. The material distribution system can be explained as the printer's extruder system. This system is the system that carries out the flow of dense fluid material from the tip called the "nozzle". The material mixer consists of a pump that sends the material to the nozzle, a hose extending from the mixer and pump to the printer tip, and finally a tip system where the material is shaped and removed. The material distribution system will be connected to frames that follow different movements and directions according to the printer types or a fixed rotating system. Finally, there is a controller section consisting of a screen or machine system where the moving parts of the printer and the material distribution system are controlled. This system is a system that will be useful in directing and monitoring the printer [10].

Contour Crafting (CC), the first known 3D concrete printing technique, and this technique was used by the Khoshnevis in the late 1980s. CC is a layered production technology with significant potential in the automatic production of small structures and the study in CC method conducted is shown in Figure 1 [16]. Khoshnevis argues that an entire structure with different designs can be built with the Contour Crafting (CC) method. This method stands out as a layered production technology that provides high efficiency, especially in the automated production of small structures that include some subcomponents. The inventor of the method states that fully functional houses with different designs can be built with CC and that this technology can also be used in the production of thousands of different small parts [16]. The contouring method involves depositing building material to create a large-scale 3D model with a smooth surface finish. It moves back and forth to extrude the concrete layer by layer. The material is extruded as the nozzle moves along the walls of the structure. It is troweled using a computer-controlled trowel that can move horizontally and vertically to ensure smooth and uniform surfaces are produced [35].

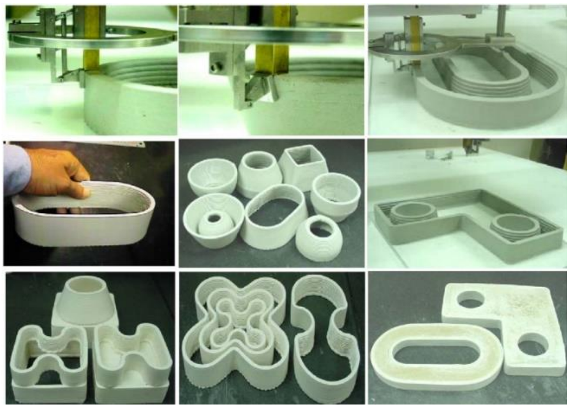

Figure 1: Contour Crafting Technique by Khoshnevis [16]

In 2007, Loughborough University developed one of the methods inspired by 3D concrete printing techniques in the construction industry, introducing the concept of 'Freeform Construction [36]. One of the main advantages of this method is that it eliminates the need for formwork during the construction process, which significantly reduces costs. Concrete Printing technology makes the production process more efficient by eliminating the use of formworks. Unlike Contour Crafting, this technique does not use a trowel and requires a finer resolution to achieve high levels of three-dimensional flexibility. Although this enables the precise control and production of complex geometries, it may result in higher production costs [37]. Concrete Printing may have certain disadvantages compared to Contour Crafting. If a smooth surface is desired after the printing process, manual troweling or grinding is required. Since this step is performed manually, it contradicts the principles of automation and represents a disadvantage compared to Contour Crafting [37]. An image of the production phase of the Concrete Printing Method is presented in Figure 2 [38].

Figure 2: Concrete Printing Method [38]

The D-Shape method, developed by Enrico Dini, differs from the previously mentioned methods by utilizing powder and adhesive layers instead of a cement-like paste. Following a programmed trajectory, the nozzle head extrudes an adhesive fluid into the sand-bed. The extruded material begins to solidify under the influence of the reaction. In the ongoing process, a new layer is added, and the process is repeated, ensuring deposition on the surface. The D-Shape method demonstrated its capabilities by 3D printing the Radiolaria Pavilion with complex geometry in 2008 and the Ferreri house in 2010 [39]. Examples of studies conducted using the D-Shape method are illustrated in Figure 3 [39].

Figure 3: D-Shape Method by Enrico Dini [39]

CC, Concrete Printing and D-Shape techniques, which have different aspects and advantages, are also used for different applications and materials. For this reason, unlike there being a competition between them, they provide different opportunities for different designs [40].

In 2014, 3D Print Canal House in Amsterdam was the first project to be completed entirely using 3D printing technology. A large-scale 3D printer called KamerMaker is used to produce the components of the house. The manufacturing process is similar to the technique used in most 3D printers. The first step begins on a computer by preparing models in the relevant 3D design program and converting them into a suitable format. The thermoplastic material used (in this case biodegradable plastic) is heated by the printer until it reaches a processable liquid state. It is then deposited in a controlled manner through the printer nozzle. As each layer is completed, the next layer is built on top of the previous one [41]. The final version of the Canal House in Amsterdam project is depicted in Figure 4 [41].

Figure 4: Canal House in Amsterdam [41]

WinSun Decoration Design Engineering Co. is a China-based company working on the development of concrete-like materials suitable for 3D printing technology. In 2014, they succeeded in producing houses built with 3D printing technology. This process is based on the principle of pre-producing building components with a 3D printer and then assembling them on site [41]. 10 of these structures, considered as a prototype, were produced in 24 hours. An example of a 3D prototype house designed by WinSun is presented in Figure 5 [41].

Figure 5: Houses produced with a 3D printer designed by WinSun as a prototype [41]

Between 2014 and 2015, WinSun successfully 3D printed a multi-story apartment building using a massive 3D printer measuring 20 feet in height, 33 feet in width, and 132 feet in length. The printer utilized recycled construction materials combined with patented technology to create the structure. Components were printed in a factory and after printing, they were being transported to the building site and assembled together to create whole construction [41]. This achievement highlights one of the notable applications of 3D printing in concrete construction. A large-scale 3D printer was employed to deposit concrete layers based on a digital design. While innovative in its approach, the resulting structure closely resembled traditional concrete buildings in its aesthetic and form [42]. An image of the multi-story building designed by WinSun is presented in Figure 6 [41].

Figure 6: Multi-story buildings printed by WinSun [41]

In 2016, WinSun company created the first 3D-printed office building for the Dubai Future Foundation, an organization established to drive innovation and shape the future of key strategic sectors through collaboration between the government and private enterprises [43]. All elements of the structure, called the "Office of the Future" and currently serving as the residence of the Emirates

Foundation, were produced in a total of seventeen days and assembled in two full days [10]. The first office in the world constructed using 3D printing technology, the 'Office of the Future' in Dubai, is shown in Figure 7 [43]. The Office of the Future is the world's first fully functional building built with 3D printing technology. This 250-square-meter structure has a design focused on energy efficiency and sustainability with meeting rooms, a café, recreation areas and modern office spaces. It minimizes the need for artificial lighting and air conditioning by using natural light to the maximum extent, while providing user comfort with large shade areas.

Figure 7: The first office in the world constructed with 3D printer technology (Office of the Future in Dubai) [43]

In 2016, Madrid unveiled the world's first large-scale 3D-printed concrete pedestrian bridge, designed by the Institute of Advanced Architecture of Catalonia (IAAC) in collaboration with D-Shape technology and constructed by Acciona with a multidisciplinary team of architects, engineers, and municipal representatives. The bridge, measuring 12 meters in length and 1.75 meters in width, was constructed using micro-reinforced concrete, printed in segments, assembled, transported, and installed on-site in compliance with regulatory standards. This structure, recognized as the world's first large-scale 3D-printed concrete pedestrian bridge, is shown in Figure 8 [44]. The design of the project was influenced by the size limitations of the 3D printer, with parametric design techniques optimizing material distribution and minimizing waste through the recycling of raw materials. Computational algorithms ensured material was used only where necessary, maximizing structural performance and enabling creative design flexibility [44].

Figure 8: The world's first large-scale 3D-printed concrete pedestrian bridge [44]

In September 2017, BAM Infrastructure group, in collaboration with Eindhoven University of Technology, completed and assembled the world's first 3D printed bicycle bridge in the Netherlands. The project began in June 2017 with the planning and design of the printing process. Measuring 8 meters in length and 3.5 meters in width, the bridge stands as a unique example in the Netherlands. The bridge components were printed separately and then integrated with prestressed and reinforced concrete. Bicyclists use this bridge to cross a canalized river called the Peelsche Loop [45]. The first 3D printed bicycle bridge produced in the Netherlands is given in Figure 9 below [45].

Figure 9: The first 3D printed bicycle bridge [45]

GAIA indicated in Figure 10 [46] is the World's First 3D Printed Mud House; Developed by WASP, the Gaia 3D house was built in the town of Massa Lombarda, located in the Emilia-Romagna region of Italy, and the project was completed in 2018. The construction took approximately 10 days, and a special 3D printer called Crane WASP was used in the construction of the house. This printer created the walls by processing a mixture of local soil, rice husk, rice straw and hydraulic lime in layers. The project aimed to present a sustainable building model that encourages the use of natural materials and local resources [46].

Figure 10: GAIA Project [46]

In 2019, ICON started producing 3D printed house for homeless people in Mexico and Austin, Texas. They use a proprietary concrete mix and 3D printers for construction. The concrete formula was designed to be accessible and made from widely available resources, potentially reducing the carbon footprint of concrete production and transportation. The homes were primarily 3D-printed with traditional framed roofs integrated into the design. In Mexico, the designs for low-income housing also feature complex elements, such as curved corners, made possible by 3D printing. ICON has built homes for low-income communities, homeless individuals, and even higher-end houses and a sample of these houses is shown in Figure 11 [47].

Figure 11: ICON’s 3D printed house for homeless people [47]

Humanity’s dream of becoming a multi-planetary species has returned to the agenda. 3D printing technology is being tested to build the first human habitat on a different planet. The Mars Dune Alpha project was launched in 2019 as a joint initiative of ICON and NASA. Within the scope of this project, it was planned to create an environment simulating life on Mars at NASA’s facilities in Houston, Texas and to prepare for long-term human missions to Mars [48]. This project uses ICON’s Vulcan 3D technology to create a concrete-like material called “Lavacrete.” This material was specifically developed to imitate Martian soil. The habitat was designed by NASA and Bjarke Ingels Group (BIG) to optimize human experience and living. An illustration of the habitat is shown in Figure 12. The project also aims to collect critical data for potential life on Mars by allowing teams to conduct simulated spacewalks and scientific research [49], [50].

Figure 12: 3D printing habitat [50]

The world’s longest 3D-printed concrete bridge was opened in China in 2019, An image of the bridge is shown in Figure 13 [44]. The 26.3-meter-long and 3.6-meter-wide pedestrian bridge is located in the Wisdom Bay Industrial Park in China in mid-January 2019. The project was developed by a team from the School of Architecture at Tsinghua University in Beijing, led by Professor Xu Weiguo. The bridge is a prime example of the potential of 3D printing in construction and demonstrates how faster and more efficient construction methods can be implemented. Through this project, China has become an international example for the widespread application of 3D-printed concrete bridges in future construction projects [44].

Figure 13: The world’s longest 3D-printed concrete bridge [44]

Designed for Dubai Municipality in the United Arab Emirates, the building was completed by Apis Cor in December 2019. At the time, it was recognized as the world's largest structure constructed using 3D printing technology. Covering an area of 640 square meters and reaching a height of 9.5 meters, the building was specifically designed to function as an office space. During construction, Apis Cor utilized specialized machines capable of operating in open construction environments and lifting structural components with crane assistance. This approach allowed for efficient and precise execution of the Project [10]. An image of the Dubai Municipality Office is shown in Figure 14 below [10].

Figure 14: Dubai Municipality Office in the United Arab Emirates [10]

Italian 3D printing company WASP has developed a variety of 3D printed homes using environmentally friendly and locally sourced materials. Among these projects, TECLA House in Figure 15 [47], which began construction in 2019, were built with soil-based materials obtained from the construction site. The soil used was blended with binders and natural fibers to form the building material and the homes were manufactured on site [47].

Figure 15: TECLA House [47]

In 2020, the Chinese architectural 3D printing company Winsun has successfully executed a remarkable project showcasing its rapid production capabilities. Project is given in Figure 16 [51]. The company manufactured portable isolation rooms in as little as two hours, completing a total of 15 rooms within a single day. These rooms were produced using 3D printing technology with a combination of concrete and recycled solid waste, achieving both material efficiency and an environmentally friendly approach. The printed isolation rooms passed environmental impact assessments and demonstrated reliability in terms of durability. Winsun deployed these rooms at Xianning Central Hospital in Hubei Province, making a significant contribution to the fight against the pandemic [51].

Figure 16: 3D printed isolation room in China [51]

Tor Alva, or the White Tower, is a 3D printed structure being built in the village of Mulegns in the Swiss Alps. Expected to be the world's tallest 3D printed structure, the tower will stand around 30 meters tall and will consist of 32 branched Y-shaped columns. Each column will have unique dimensions, consisting of large wavy ribs and textures of smaller materials. The 3D printing method used in the construction of the tower eliminates the need for molds and allows architects to experiment with shapes, surface parts and molds. The tower will also be the first example of compressed concrete used as a fully flexible structure, with steel reinforcement incorporated during the robotic production process. Tor Alva will consist of six floors and will offer "abstract, atmospherically dense spaces that extend from dark and closed spaces below to airy rooms above." The tower will host music and theater performances. These products include economic and ecological policies, as well as the possibility of an elaborate and non-standard architecture with a bold wealth of shapes. The project's design was led by architects Benjamin Dillenburger and Michael Hansmeyer of ETH Zurich's Digital Building Technologies group [52]. Tor Alva is expected to be completed in 2025. Figure 17 shows the process, assembly and planned completion [52].

Figure 17: The photos are the printing process, assembly and design of Tor Alva, respectively [52]

US company Printed Farms has completed a horse stable described as 'luxury' by the end of 2023. As seen in Figure 18 [53] the special feature of this project is its size: by repositioning the fixed frame-based BOD2 portal printer from COBOD, the manufacturer was able to print a building of around 1000 m^2, beating the previous record set in the Middle East by 50%. This structure is described as the largest 3D printed structure in the world and its cost is stated to be around $3,000,000-3,500,000 [53].

Figure 18: Horse Barn by Printed Farms [53]

IV. DISCUSSION

With the integration of 3D printing technology into the construction sector, some positive and negative impacts have emerged. Considering all these impacts, some discussions have also come to the fore regarding the existence of 3D concrete printing technology in the construction sector. When some important studies in literature are examined, their positive and negative effects will be explained under the title of discussion. The general positive effects of this technology include a faster construction process, potential solutions for post-disaster reconstruction, reduction of material waste, design freedom by eliminating the need for formworks, cost savings on formworks, less waste material, and reduced risk for workers in hazardous areas. In addition to the positive effects, the initial high investments in machinery and software, scale restrictions, the lack of legal regulations and international standards, the lack of personnel to work in the technological field and the decrease in labor employment in the future are among the negative effects. Figure 19 [45] clearly illustrates the different stages in the process of building a structure using traditional methods. These stages require the use of labor at various points in the structure, making the process both time-consuming and costly [45].

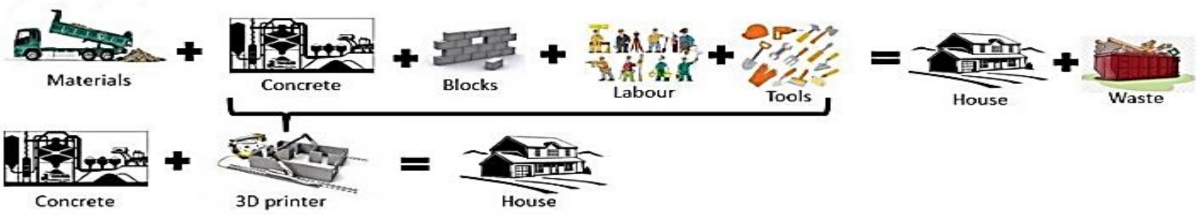

Figure 19: Traditional method vs 3D print method [45]

Time is a critical factor in construction projects. Reducing the construction duration enables clients to commence operations sooner, facilitates early revenue generation, lowers overhead costs, and frees up resources for other projects more quickly. 3D printing enables significantly faster construction, surpassing the speed of traditional methods [43]. 3D printing technology in construction can significantly increase speed and reduce project timelines. Sakin and Kiroglu [54] reported that a 400-square-meter house was built in just 24 hours. Similarly, the Chinese company Winsun successfully printed 10 full-scale houses in less than a day [55]. A simulation model of contour crafting predicted that a custom-designed 200-square-meter house could be printed in under 20 hours. The same model also demonstrated that constructing the same house using traditional methods would take nearly three times longer due to the time-intensive processes of installing and removing formwork, as well as waiting for the concrete to cure before proceeding [56].

The substantial waste generated by the construction industry represents a significant challenge. Formwork is a major source of this waste, as it is entirely discarded at the end of its lifecycle, contributing to the increasing waste production in the construction sector. A notable finding from Llatas's research indicates that the construction sector accounts for nearly 80% of global waste production [57]. Integrating 3D-printed structures into architectural projects provides an environmentally conscious alternative. These structures require significantly less energy and generate approximately 30% of the waste produced by traditional construction methods [58]. Furthermore, since additive manufacturing eliminates the need for formwork, waste associated with wooden molds is entirely avoided. Instead, structures are built directly on-site, layer by layer, minimizing both material waste and environmental impact. For example, avoiding the use of wooden molds in concrete casting helps reduce timber consumption, further lessening ecological damage [59].

From a different perspective, the substantial amount of waste generated by the construction industry represents a significant challenge. Formwork is a major source of this waste, as it is entirely discarded at the end of its lifecycle, contributing to the increasing waste production in the construction sector. A notable finding from Llatas's research indicates that the construction sector accounts for nearly 80% of global waste production [57]. Integrating 3D-printed structures into architectural projects provides an environmentally conscious alternative. These structures require significantly less energy and generate approximately 30% of the waste produced by traditional construction methods [58]. Furthermore, since additive manufacturing eliminates the need for formwork, waste associated with wooden molds is entirely avoided. Instead, structures In addition to environmental benefits, eliminating formwork also allows for unprecedented freedom in geometric design. Unlike conventional techniques, 3D printing enables architects and engineers to create intricate and unconventional designs with ease. Curved structures, which are typically expensive and challenging to construct using traditional methods, can be efficiently produced through 3D printing. This flexibility not only supports innovative architectural designs but also bridges the gap between architecture and art. For instance, the 3D-printed house developed by 3D Printhuset in Denmark in Figure 20 [61] exemplifies this potential, featuring curved elements and unique geometries while maintaining structural integrity. This allows architects to approach the design process more creatively and innovatively. It also encourages the combination of art and architecture [60].

Figure 20: 3D printed house printed by 3D Printhuset in Denmark [61]

Working on construction sites and in production areas presents various challenges and working conditions that put workers' health at risk. The high accident rate in the construction industry is largely attributed to its unique working conditions. Construction differs from other sectors because each project has unique requirements, sites are large and dispersed, and the working conditions vary, leading to various risks. Working outdoors most of the time introduces numerous hazards. Work areas are highly exposed to external factors and dangers and are greatly influenced by weather conditions [62]. The adoption of 3D printing in construction could reduce the amount of labor required [63]. Based on this, the Singaporean government believes the technology will help reduce the country's reliance on foreign labor [64]. As the labor requirement decreases, a lower risk of injury is expected. Sakin and Kiroglu [54] believe that the adoption of 3D printing in the construction sector will lead to a reduction in injuries and fatalities on construction sites.

For a new concrete construction project, slightly more than half of the total cost is allocated to formwork labor, followed by 30% to concrete materials, 10% to formwork materials, and 7% to additional concrete materials, as illustrated in Figure 21 [64]. The use of 3D printing in construction eliminates the need for formwork entirely. For instance, the cost of a full-scale house printed by Winsun Company cost as little as $4,800 [65] while a 400 ft^2 house printed by Apis Cor company cost only $10,000 [54]. The standard cost allocation for new concrete construction projects using traditional methods and 3D printing technology are compared in Figure 21. The 3D printing data was acquired from a construction 3D printing project carried out by Zhengzhou Dingsheng Company Ltd in China, as shown in Figure 22 [63]. In this project, the energy consumption for 3D printing represented only 0.2% of the total cost, making it negligible, as illustrated in Figure 21 [63].

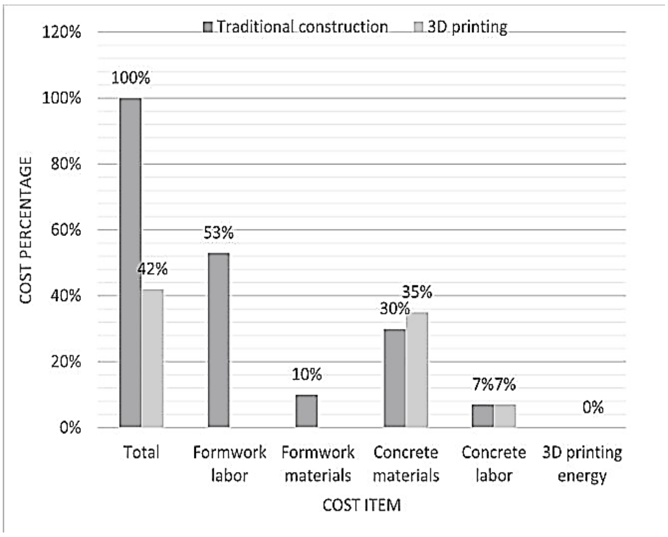

Figure 21: Cost percentage comparison of 3D printing technology and traditional method [63]

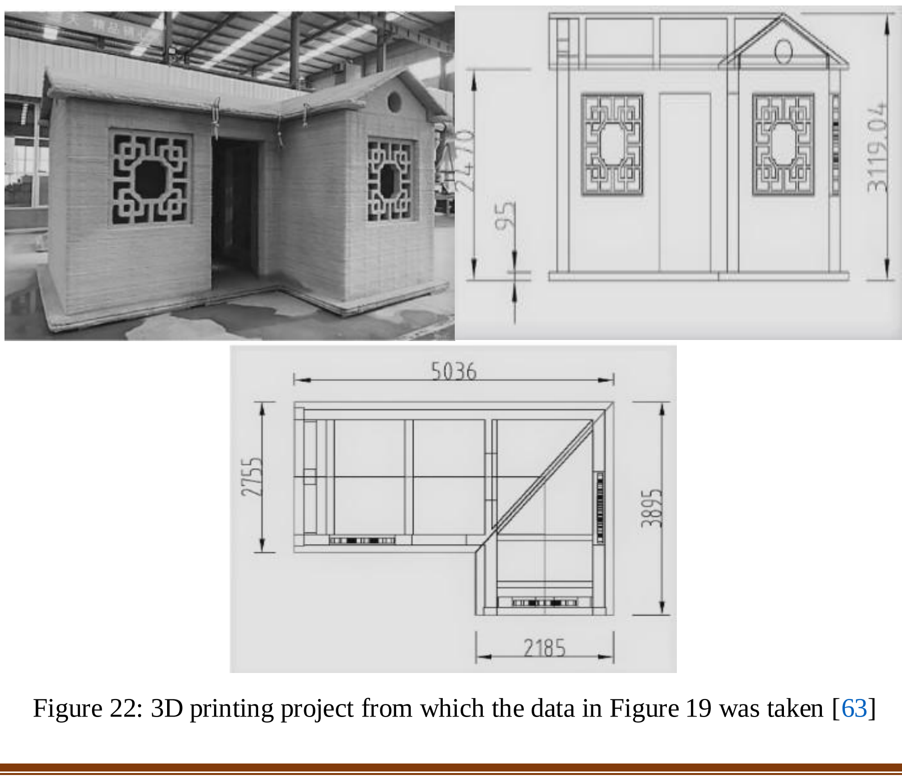

Figure 22: 3D printing project from which the data in Figure 19 was taken [63]

In a case study involving a 3D-printed office in Dubai, the workforce included seven individuals for installing construction components, ten electricians and MEP (Mechanical, Electrical, and Plumbing) professionals, and one person to operate the printer. The labor costs for this office were 60% lower than those of a conventional structure of comparable size [61]. Additionally, the 3D printing construction method demonstrated reduced labor-intensive processes across various sectors of construction compared to traditional methods [66].
While construction automation has garnered significant attention, some researchers argue that 3D printing is a complementary technology in the construction industry and will not replace existing methods [67].
Scalability is a common issue for most existing 3D printing processes, as the size of the design is limited by the volume of the printer's chamber. This issue is more pronounced in the building and construction industry, where it is impractical to have printers that are larger than actual buildings [66]. 3D printing faces the challenge of not yet being prepared for large-scale projects. Additionally, automated construction is not well-suited for producing large-scale products [68].
The absence of established codes and standards for 3D printing in construction presents a significant challenge. For any design, it is essential to comply with all relevant construction requirements; however, applying 3D printing technology in a way that adheres to these guidelines is difficult due to the lack of regulations specific to its use in construction. This regulatory gap creates further issues, as there are no clear rules for integrating 3D printing into the construction process. As a result, it is challenging to ensure the technology complies with existing construction codes. Additionally, additive manufacturing (AM) could impact current laws and regulations, potentially requiring adjustments to existing legal frameworks or the creation of entirely new laws to accommodate its use. Currently, 3D-printed building structures are largely experimental, as further research is needed to define the properties of printing materials, refine construction techniques, and align them with existing building code standards [69]. In China, several companies are collaborating with the national construction standards department to update the construction guidelines to incorporate 3D printing [70]. The existing 3D-printed building structures are experimental, as additional research is needed to define the properties of printing materials, clarify construction practices and printing processes, and integrate them into existing building code regulations [43].
The demand for labor is lower when constructing a building with a 3D printer, as technology takes over tasks that are usually carried out by human workers [43]. While this offers advantages in terms of reducing labor costs, it may also result in fewer job opportunities for workers in the construction industry. Some researchers have noted that the decreased need for labor could have politically destabilizing effects on certain economies [71]. A significant challenge is that the construction industry relies heavily on high-skill, labor-intensive traditional processes, making it difficult to adopt automation technologies [72]. Construction workers will need to acquire new skills to integrate 3D printing into the building process. These skills encompass the installation, operation, management, and maintenance of 3D printers. However, on a typical construction site, these essential abilities, which are key to ensuring the success of a project, are not readily available [61]. Training for 3D printing in construction becomes even more difficult in remote communities where literacy and numeracy are significant challenges [73], and in many instances, English is not the primary language [61]. Additionally, the lack of experience with construction technology will result in slow adoption of new technologies within local communities.
One drawback is the high initial cost, as 3D printing is currently an expensive construction method. The initial cost of the equipment is higher than that of other machines typically used in construction. This extra cost associated with 3D printing equipment presents a potential risk to the project [74]. The equipment itself can be costly, and transporting the printer is both challenging and relatively expensive. For the concrete to flow through the robot's nozzle, it must be workable, requiring a higher slump than conventional concrete. This may necessitate using a weaker or more expensive type of concrete. Additionally, in remote areas, the total project cost not only depends on typical construction factors but also on variables such as the location, the amount of local materials used, and the number of local workers. Therefore, case studies are needed to compare the final costs of remote housing projects using 3D printing versus traditional methods [61]. Ghaffar, Corker and Man [75] noted that large-scale printers are costly, and the ongoing need for maintenance adds to the expense. However, this cost is expected to decrease as industrial competition increases.

V. CONCLUSION

As a result, 3D concrete printing technology offers significant advantages that could open a new era in innovation in the field of construction. Among the key benefits, the rapid construction capability stands out, enabling faster project completion, particularly in emergency situations like earthquakes. Today, the elimination of molds creates more freedom, originality and creativity in designing structures with complex geometry without being stuck with the limitations of traditional methods that are widely used. In addition, 3D printing technology allows for more economical use of materials, thus contributing to environmental sustainability and reducing material waste. One of the most significant impacts in the field study has been on the risk in the work environment. Replacing humans with machines for dangerous tasks on construction sites helps keep workers away from hazardous conditions. This also protects workers' health and safety. Furthermore, minimizing formwork costs offers significant cost savings, especially in large-scale construction projects.
However, while this technology provides significant contributions, it also brings with it some challenges and disadvantages. The high initial investment required for the machine elements and the software that runs it can be a deterrent for small businesses to start. The scalability limitations restrict the size and capabilities of the printers, posing challenges for very large-scale structures. The lack of formal regulations and international standards for using 3D concrete printers in construction also presents risks, as existing regulations do not always align to integrate this technology effectively. Considering its active use in the field, 3D concrete printing technology, being relatively

new, suffers from a lack of trained personnel to manage and operate it. Considering the multi-million-dollar projects and sensitive technology, it is essential to have experts in this field. The biggest problem among the negative effects will be the reduction in labor demand. This technology, which is expected to reduce employment in construction in the long term, is increasingly encouraging automation and mechanization to some extent.

Considering all the positive and negative effects, despite all these difficulties, the benefits of 3D concrete printing technology have the capacity to create a revolution in the medium and long term. As progress continues, the benefits will outweigh the disadvantages, and the construction process is likely to advance much further in terms of construction, economy, ecology and safety.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] "The night I invented 3D printing" | CNN Business'. Accessed: Nov. 01, 2024.. Available from: https://shorturl.at/55DGN

[2] F42 Committee, Terminology for Additive Manufacturing Technologies Available from: https://shorturl.at/MHlMY.

[3] S. Ö. Felek, 'Mimari Yapilarda 3 Boyutlu Yazicilarin Kullanimi,' International Journal of 3D Printing Technologies and Digital Industry, vol. 3, no. 3, pp. 289-296, 2019. Available from: https://shorturl.at/t3WRd

[4] Tümer, M. B. (2020). Üç Boyutlu Yazicilar Ve Günümüz Mimarisinde Kullanimi. Master's Thesis, Işık University, Istanbul.

[5] Y. Bai and C. B. Williams, 'An exploration of binder jetting of copper', Rapid Prototyping Journal, vol. 21, no. 2, pp. 177–185, Mar. 2015, https://shorturl.at/DZKFF.

[6] '[7]Guide to Selective Laser Sintering (SLS) 3D Printing', Formlabs. Accessed: Nov. 02, 2024. Available: https://formlabs.com/asia/blog/what-is-selective-laser-sintering/

[7] R. Udroiu, 'Additive Manufacturing Technologies Used for Superalloys Processing', 2014.

[8] C. W. Hull, 'Method for production of three-dimensional objects by stereolithography', US4929402A, May 29, 1990 Accessed: Nov. 02, 2024. Available: https://patents.google.com/patent/US4929402A/en

[9] A. Akpek, 'Stereolitografi ile üç boyutlu (3B) olarak biyobaskılanmış yapay kalp kapakçıklarının biyouyumluluk özelliklerinin analizi', Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, vol. 2018, no. 2018, Apr. 2018, Available: https://shorturl.at/6p2uR.

[10] A. Yılmaz, *Afet Sonrası Oluşacak Barınma İhtiyacını 3 Boyutlu Yazıcı Teknolojileri ile Çözümleme Üzerine Bir Değerlendirme*, Master's thesis, Fatih Sultan Mehmet University, Istanbul, 2022.

[11] J. Mireles, D. Espalin, D. Roberson, B. Zinniel, F. Medina, and R. Wicker, 'Fused Deposition Modeling of Metals', Aug. 2012. Available: https://shorturl.at/TLKOI

[12] D. ÇeliK and K. ÇetiNkaya, 'ÜÇ BOYUTLU YAZICI TASARIMLARI, Prototipleri Ve Ürün Yazdirma Karşilaştirmalari'. İleri Teknoloji Bilimleri Dergisi, vol. 5, no. 2, Jul. 2016

[13] A. İ. Akbaba and E. Akbulut, "3 Boyutlu Yazıcılar ve Kullanım Alanları / 3D Prınters And Areas of Usage," ETU Sentez Iktisadi ve Idari Bilimler Dergisi, Erzurum Teknik Universitesi, no. 3, pp. 19–46, Mar. 2021, Available: https://doi.org/10.47358/sentez.2021.13.

[14] 'Technical Considerations for Additive Manufactured Medical Devices - Guidance for Industry and Food and Drug Administration Staff'.

[15] J. Pegna, 'Exploratory investigation of solid freeform construction', Automation in Construction, vol. 5, no. 5, pp. 427–437, Feb. 1997. Available: https://doi.org/10.1016/S0926-5805(96)00166-5

[16] B. Khoshnevis, 'Automated construction by contour crafting—related robotics and information technologies', Automation in Construction, vol. 13, no. 1, pp. 5–19, Jan. 2004, Available: https://doi.org/10.1016/j.autcon.2003.08.012.

[17] S. Lim et al., 'Development of a Viable Concrete Printing Process', presented at the 28th International Symposium on Automation and Robotics in Construction, Seoul, Korea, Jun. 2011. Available:: https://shorturl.at/s2TJ2.

[18] A. Tibaut, D. Rebolj, and M. Nekrep Perc, 'Interoperability requirements for automated manufacturing systems in construction', J Intell Manuf, vol. 27, no. 1, pp. 251–262, Feb. 2016, Available: https://shorturl.at/5YDxh.

[19] S. Kökhan and U. Özcan, '3D Yazıcıların Eğitimde Kullanımı, vol. 2, no. 1, pp. 80–85, May 2018

[20] S. Ford and T. Minshall, 'Invited review article: Where and how 3D printing is used in teaching and education', Additive Manufacturing, vol. 25, pp. 131–150, Jan. 2019, Available: https://doi.org/10.1016/j.addma.2018.10.028.

[21] S. C. Joshi and A. A. Sheikh, '3D printing in aerospace and its long-term sustainability', Virtual and Physical Prototyping, vol. 10, no. 4, pp. 175–185, Oct. 2015, Available:: https://doi.org/10.1080/17452759.2015.1111519.

[22] Y.-C. Wang, T. Chen, and Y.-L. Yeh, 'Advanced 3D printing technologies for the aircraft industry: a fuzzy systematic approach for assessing the critical factors', Int J Adv Manuf Technol, vol. 105, no. 10, pp. 4059–4069, Dec. 2019, Available: https://shorturl.at/fDPUr

[23] A. Uriondo, M. Esperon-Miguez, and S. Perinpanayagam, 'The present and future of additive manufacturing in the aerospace sector: A review of important aspects', Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, vol. 229, no. 11, pp. 2132–2147, Sep. 2015, Available: https://doi.org/10.1177/0954410014568797.

[24] N. Kara, 'Havacilikta Katmanli Imalat Teknolojisinin Kullanimi', Mühendis ve Makina Dergisi, vol. 54, no. 636, pp. 70-75, 2013.

[25] N. Shahrubudin, T. C. Lee, and R. Ramlan, 'An Overview on 3D Printing Technology: Technological, Materials, and Applications', Procedia Manufacturing, vol. 35, pp. 1286–1296, 2019, Available: https://doi.org/10.1016/j.promfg.2019.06.089.

[26] N. Arslan, B. Yaylaci, N. D. Eyüpoğlu, and M. Kürtüncü, 'Sağlikta Gelişen Teknoloji: Üç Boyutlu Yazicilar', 2 International Journal of 3D Printing Technologies and Digital Industry, vol. 2, no. 2, pp. 99–110, Jul. 2018.

[27] K. Demir, E. B. Kuzu Demir, C. Çaka, U. Tuğtekin, H. İslamoğlu, and A. Kuzu, 'Üç Boyutlu Yazdırma Teknolojilerinin Eğitim Alanında Kullanımı: Türkiye'deki Uygulamalar', Ege Eğitim Dergisi, vol. 2, no. 17, pp. 481–481, Dec. 2016, Available: https://shorturl.at/yPluL.

[28] I. Dankar, M. Pujolà, F. El Omar, F. Sepulcre, and A. Haddarah, 'Impact of Mechanical and Microstructural Properties of Potato Puree-Food Additive Complexes on Extrusion-Based 3D Printing', Food Bioprocess Technol, vol. 11, no. 11, pp. 2021–2031, Nov. 2018, Available: https://shorturl.at/MPFy6.

[29] E. A. Aldanmaz and R. Sever, 'Gıdaların Dizaynında 3 Boyutlu Yazıcı Teknolojisi Uygulamaları'.

[30] F. C. Godoi, S. Prakash, and B. R. Bhandari, ‘3d printing technologies applied for food design: Status and prospects’, Journal of Food Engineering, vol. 179, pp. 44–54, Jun. 2016, Available:: https://doi.org/10.1016/j.jfoodeng.2016.01.025.
[31] ‘HTML’. Accessed: Nov. 03, 2024. Available: https://rtejournal.de/rte/article/download/2013_1/235?inline=1
[32] D. E. Düzgün and K. ÇetiNkaya, ‘Moda Alaninda 3 Boyutlu Baski Teknolojileri Kullanimi’, International Journal of 3D Printing Technologies and Digital Industry, vol. 3, no. 1, pp. 19–31, Apr. 2019.
[33] M. Yıldıran, ‘Moda Giyim Sektöründe Üç Boyutlu Yazicilarla Tasarim Ve Üretim, Art-E Sanat Dergisi, vol. 9, no. 17, pp. 155-172, 2016.
[34] A. Vanderploeg, S.-E. Lee, and M. Mamp, ‘The application of 3D printing technology in the fashion industry’, International Journal of Fashion Design, Technology and Education, vol. 10, no. 2, pp. 170–179, May 2017, doi: https://doi.org/10.1080/17543266.2016.1223355
[35] Ayşe Karoğlu, “Selülozik Katkilarin Sürdürülebilir 3d Beton Üretiminde Kullaniminin Incelenmesi,” İnşaat Mühendisliği Anabilim Dalı, Konya Teknik Üniversitesi Lisansüstü Eğitim Enstitüsü, 2023,
[36] R. A. Buswell, R. C. Soar, A. G. F. Gibb, and A. Thorpe, ‘Freeform Construction: Mega-scale Rapid Manufacturing for construction’, Automation in Construction, vol. 16, no. 2, pp. 224–231, Mar. 2007, Available : https://doi.org/10.1016/j.autcon.2006.05.002.
[37] F. Bos, R. Wolfs, Z. Ahmed, and T. Salet, ‘Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing’, Virtual and Physical Prototyping, vol. 11, no. 3, pp. 209–225, Jul. 2016, Available : https://doi.org/10.1080/17452759.2016.1209867
[38] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, ‘Mix design and fresh properties for high-performance printing concrete’, Mater Struct, vol. 45, no. 8, pp. 1221–1232, Aug. 2012, https://shorturl.at/LFvpo.
[39] B. Nematollahi, M. Xia, and J. Sanjayan, ‘Current Progress of 3D Concrete Printing Technologies’, presented at the 34th International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, Jul. 2017. doi: https://shorturl.at/aVw6R.
[40] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. F. Gibb, and T. Thorpe, ‘Developments in construction-scale additive manufacturing processes’, Automation in Construction, vol. 21, pp. 262–268, Jan. 2012, Available : https://doi.org/10.1016/j.autcon.2011.06.010.
[41] I. Hager, A. Golonka, and R. Putanowicz, ‘3D Printing of Buildings and Building Components as the Future of Sustainable Construction?’, Procedia Engineering, vol. 151, pp. 292–299, 2016, Available : https://doi.org/10.1016/j.proeng.2016.07.357.
[42] N. O. E. Olsson, E. Arica, R. Woods, and J. A. Madrid, ‘Industry 4.0 in a project context: Introducing 3D printing in construction projects’, Project Leadership and Society, vol. 2, p. 100033, Dec. 2021, Available : https://doi.org/10.1016/j.plas.2021.100033.
[43] S. El-Sayegh, L. Romdhane, and S. Manjikian, ‘A critical review of 3D printing in construction: benefits, challenges, and risks’, Archiv.Civ.Mech.Eng, vol. 20, no. 2, p. 34, Jun. 2020, Available: https://shorturl.at/0HV78.
[44] K. Friis, “3D printed concrete bridges,” Master Thesis, University of Agder, Faculty of Engineering and Science Department of Engineering Sciences, 2020.
[45] N. Nadarajah, “Development of concrete 3D printing,” Master Thesis, Building Technology, 2018.
[46] G. Sood, ‘Designed by WASP, Gaia is World’s First 3D Printed Mud House’, Homecrux. Accessed: Nov. 18, 2024. [Online]. Available: https://shorturl.at/n1GdK
[47] A. Puppos, “Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing,” Master Of Science In Architecture, The University Of Arizona,College Of Architecture, Planning & Landscape Architecture, 2021.
[48] S. Nehme and A. Abeidi, ‘3D concrete printing: review’, Epitoanyag - JSBCM, vol. 74, no. 5, pp. 183–187, 2022, Available: https://shorturl.at/YautO.
[49] ‘NASA’S Crew Health and Performance Exploration Analog & Mars Dune Alpha Habitat - NASA’. 2024. Available: https://www.nasa.gov/humans-in-space/chapea/habitat/
[50] Maneesh Js, ‘Development And Advancement Of 3d Printer And Its Impact Bachelor of Technology in Electronics and Communication Engineering CVR College Of Engineering Certificate’, 2022, Available: https://shorturl.at/9sU8W.
[51] A. Nazir et al., ‘The rise of 3D Printing entangled with smart computer aided design during COVID-19 era’, Journal of Manufacturing Systems, vol. 60, pp. 774–786, Jul. 2021, Available : https://doi.org/10.1016/j.jmsy.2020.10.009.
[52] ‘Production begins on the world’s tallest 3D printed structure’, Archinect. Accessed: Nov. 21, 2024. Available: https://shorturl.at/IU7hr
[53] P. E. Team, ‘COBOD completed the world’s largest 3D-printed horse barn in Florida’. Accessed: Nov. 21, 2024. Available: https://shorturl.at/LFNfm
[54] M. Sakin and Y. C. Kiroglu, ‘3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM’, Energy Procedia, vol. 134, pp. 702–711, Oct. 2017, Available : https://doi.org/10.1016/j.egypro.2017.09.562.
[55] T. Wangler et al., ‘Digital Concrete: Opportunities and Challenges’, RILEM Tech Lett, vol. 1, pp. 67–75, Oct. 2016, doi: 1 https://doi.org/10.1016/j.cemconres.2020.106047.
[56] C. M. Rouhana, M. S. Aoun, F. S. Faek, M. S. Eljazzar, and F. R. Hamzeh, ‘The Reduction Of Construction Duration By Implementing Contour Crafting (3D Printing)’, 22nd Annual Conference of the International Group for Lean Construction, 1031-1042, 2014.
[57] C. Llatas, ‘A model for quantifying construction waste in projects according to the European waste list’, Waste Management, vol. 31, no. 6, pp. 1261–1276, Jun. 2011, Available : https://doi.org/10.1016/j.wasman.2011.01.023.
[58] A. Saleh Abd Elfatah, ‘3D Printing in Architecture, Engineering and Construction (Concrete 3D printing)’, Engineering Research Journal, vol. 162, no. 0, pp. 119–137, Jun. 2019, Available : 10.21608/erj.2019.139808.
[59] D. Delgado Camacho et al., ‘Applications of Additive Manufacturing in the Construction Industry A Prospective Review’, presented at the 34th International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, Jul. 2017. Available: https://doi.org/10.1016/j.autcon.2017.12.031.
[60] L. Feng and L. Yuhong, ‘Study on the Status Quo and Problems of 3D Printed Buildings in China’, Global Journal of HUMAN-SOCIAL SCIENCE: H Interdisciplinary, Volume 14, Issue 5, Version 1.0, 2014.
[61] M. Bazli, H. Ashrafi, A. Rajabipour, and C. Kutay, ‘3D printing for remote housing: Benefits and challenges’, Automation in Construction, vol. 148, p. 104772, Apr. 2023, Available : https://doi.org/10.1016/j.autcon.2023.104772.
[62] A. Ercan, ‘Türkiye’de Yapı Sektöründe İşçi Sağlığı ve Güvenliğinin Değerlendirilmesi’, Journal of Polytechnic, Vol. 13 No. 1 pp. 49-53, 2010.
[63] H. Valkenaers, D. Jansen, A. Voet, Ann Van Gysel, and E. Ferraris, “Additive manufacturing for concrete: a 3D printing principle,” vol. 1, pp. 139–142, Jun. 2014.
[64] Y. Pan, Y. Zhang, D. Zhang, and Y. Song, ‘3D printing in construction: state of the art and applications’, Int J Adv Manuf Technol, vol. 115, no. 5–6, pp. 1329–1348, Jul. 2021, Available : https://shorturl.at/2Cn2l.
[65] ‘WinSun China builds world’s first 3D printed villa and tallest 3D printed apartment building | 3D Print Expo’, 3D Print Expo 2019. Accessed: Nov. 23, 2024. Available: https://shorturl.at/LEaHK

[66] X. Zhang et al., 'Large-scale 3D printing by a team of mobile robots', Automation in Construction, vol. 95, pp. 98–106, Nov. 2018, Available :https://doi.org/10.1016/j.autcon.2018.08.004
[67] Z. Dakhli and Z. Lafhaj, 'Experimental and numerical prototyping of a complex cement column formwork for construction', Architectural Engineering and Design Management, vol. 13, no. 2, pp. 147–165, Mar. 2017, Available :https://doi.org/10.1080/17452007.2016.1226745
[68] I. Perkins and M. Skitmore, 'Three-dimensional printing in the construction industry: A review', International Journal of Construction Management, vol. 15, no. 1, pp. 1–9, Jan. 2015, Available : https://doi.org/10.1080/15623599.2015.1012136
[69] E. D. J. White, A. Alhasan, and P. Vennapusa, 'Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure', Jan. 2015.
[70] 'Winsun: Revolutionizing the Construction Industry with 3D Printing', Technology and Operations Management. Accessed: Nov. 24, 2024. Available: https://shorturl.at/wuo5i
[71] T. Campbell, C. Williams, O. Ivanova, and B. Garrett, could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing, 'Strategic Foresight Initiative October, 2011.
[72] B. Khoshnevis, D. Hwang, K. T. Yao, and Z. Yeh, 'Mega-scale fabrication by Contour Crafting', IJISE, vol. 1, no. 3, p. 301, 2006, Available :https://doi.org/10.1504/IJISE.2006.009791.
[73] I. Kral, 'The literacy question in remote Indigenous Australia', National Indigenous Times, Issue. 06, 30 April 2009.
[74] 'We redefine construction', CyBe Construction. Accessed: Nov. 24, 2024. Available: https://shorturl.at/uI1In
[75] S. H. Ghaffar, J. Corker, and M. Fan, 'Additive manufacturing technology and its implementation in construction as an eco-innovative solution', Automation in Construction, vol. 93, pp. 1–11, Sep. 2018, Available : https://doi.org/10.1016/j.autcon.2018.05.005