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Additive Manufacturing in the Engineering and Construction Industry: Development and Potentiality

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Abstract

In recent years, the technology of additive manufacturing or 3D printing has been a focal point for the scientific community since it could be the solution for many big issues facing the world and has the ability to completely change our economies and industries.

Particularly, the emerging method of 3D printing in the construction sector has been under discussion for several years now and it has a bright future to integrate it with other technologies in the industry in order to solve the issues of housing, waste management, material use, and many others. However, To make this possible, we must address the technical challenges that emerged with it (like printer's physical limitations and materials formulation standardization), which means ensuring that this new technology reaches development researchers and investors all around the world so this technology reaches its expectations and we secure a suitable living environment for future generations.

Key words:

3D printing, additive manufacturing, cementitious material, construction automation

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Chapter 1
Introduction

1.1. Scope

The engineering and construction industry has always been responsible for providing human needs in terms of housing, infrastructure and architecture as it developed from our natural survival instincts.

Nowadays the E&C sector is one of the most important industries in the global economy, accounting for up to 13% of global gross domestic product GDP and employing 7% of the world's population. [1] [2]

With the critical skill shortage around the world [3] and the under-developed conventional methods still being used, the world faces an immense challenge as a result of global population growth and massive migrations: the need for affordable housing, accommodation, and services is exponentially increasing.

Furthermore, the huge impact of this sector on the environment cannot be ignored, as it is the world's biggest consumer of raw materials and responsible for 25 to 40% of global carbon emissions [4]. So, the demand for environmentally friendly construction processes necessitates a big change [5].
This means that the need for advanced technologies has now become a necessity that cannot be neglected, as it is able to reduce the material and energy use and thus reduce waste and emissions in addition to the shift towards renewable energy, which enables more valuable use of natural resources and greatly reduces the ecological impact.

Accordingly, advanced technologies in the E&C industry manifest in the digitalization step and the implementation of robotic manufacturing techniques such as 3D printing which has the potential to completely transform this sector and provide the leap needed to survive.

During the past twenty years, the interest in 3D printing has increased dramatically leading to more studies and media coverage which highlighted the importance of exploring the evolution of this technology (particularly in the construction industry) and the significance of collecting its key achievements.
Additive manufacturing techniques and especially 3D construction printing is a new tool for architects and engineers that allows them to create large-scale construction projects quickly and affordably [6] [7].

1.2. Main Objective

Exploring the development of 3D Printing particularly in the construction sector throughout the years and collecting the most important achievements in this method in order to know where the current approaches are in relation to the evolution of this technology and to evaluate its readiness for the implementation in the engineering and construction industry, as there is no a state of the art that collects this information into one work in such a way.

1.3. Secondary objectives

1- Exploring the history of 3D printing since it was an initial concept.
2- Creating an overview for the industrial adoption context of 3D construction printing.
3- Creating an overview for the state-of-the-art researches on materials and mixtures used in 3D printing, especially in construction and large structures.
4- Classifying design methodologies for the most important material in the 3DCP.

5- Creating an overview for the major 3D construction printing methods/approaches and defining the properties of each one.
6- Defining 3D printing control strategies.
7- Defining the advantages, challenges and potential applications of 3D printing in the construction sector.

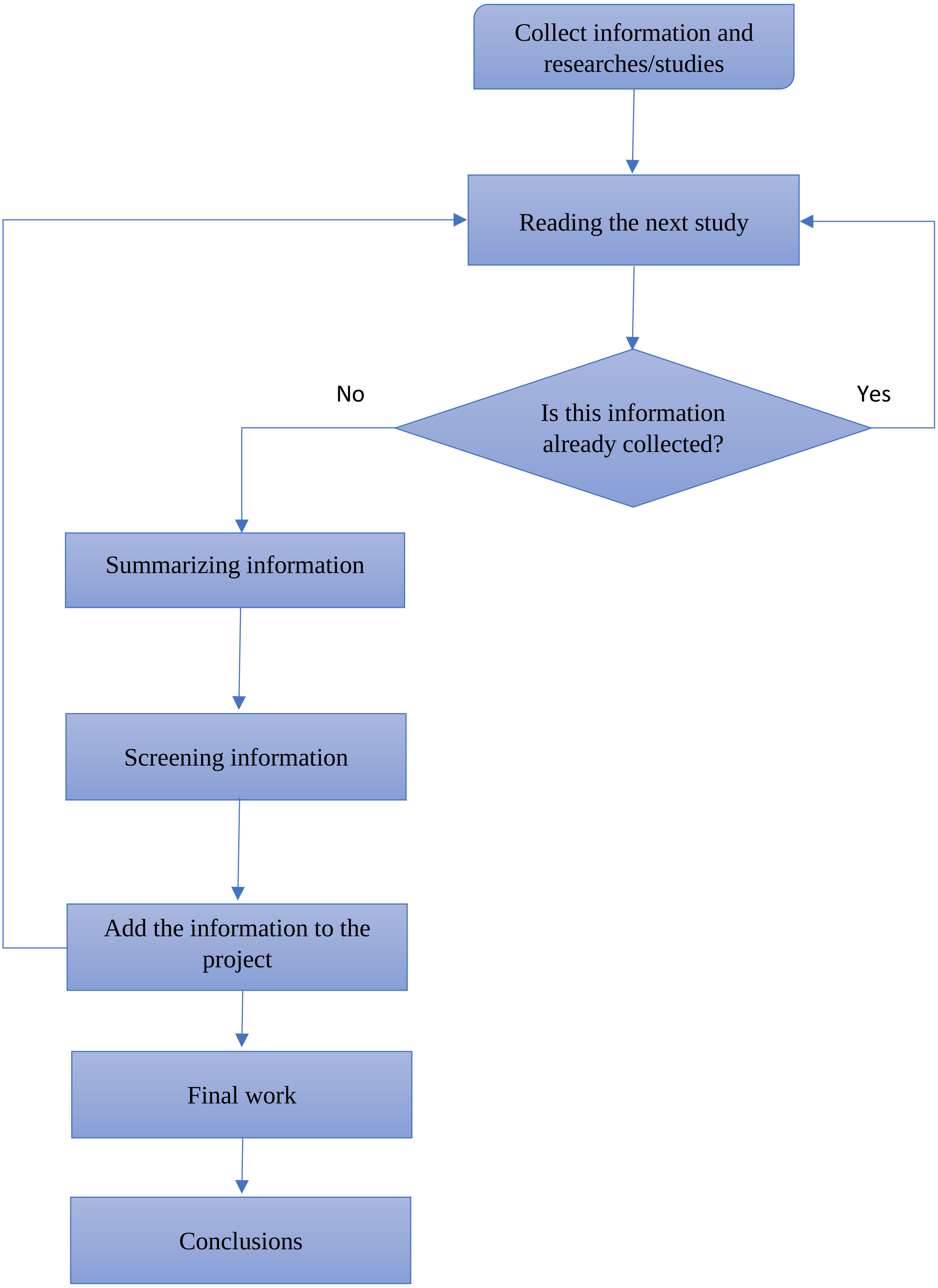


Figure 1 Methodology of work

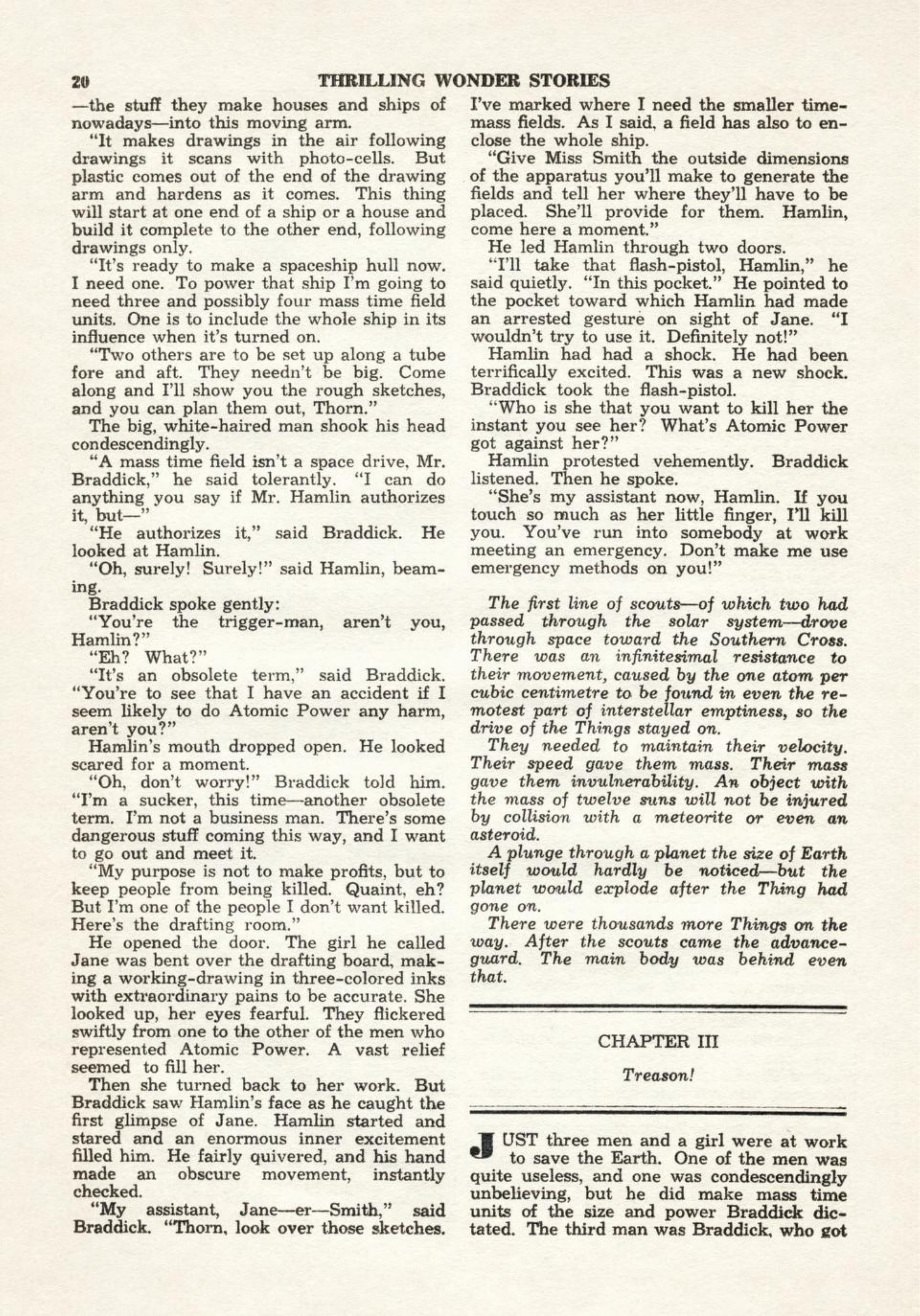
Chapter 2
Historical overviews

One of the first evidences of the idea of 3d printing sizable forms in science fiction is in the Murray Leinster's "Things Pass by" - “Thrilling Wonder Stories” v27 n02 [1945-Summer] see Figure **2** when a man builds a spaceship one layer at a time by using a moving arm spraying fictional material to make the body of the spaceship, as we see in Figure **3**, “For that reason, there aren’t any mass- production machines for big objects like ships and so on. It’s cheaper to be inefficient and flexible. But this constructor is both efficient and flexible. I feed magnetronic plastics —the stuff they make houses and ships of nowadays—into this moving arm. It makes drawings in the air following drawings it scans with photo-cells. But plastic comes out of the end of the drawing arm and hardens as it comes. This thing will start at one end of a ship or a house and build it complete to the other end, following drawings only.” [8]

It is interesting how the description of the 3d printing machine -as fictional as it was back then-have the same principles for modern day technology, describing not only the use of 3d printing in the building process but also the scanning and the use of drawings to operate the printing machine.

Figure 2 The Cover of Thrilling wonder stories **[8]**

A collection of patents by William E. Urschel, dating from the 1930s and 1940s, describe a ‘Machine for building walls,' with thorough explanations and sketches of “a machine operable to mould a solidifiable material into the form of a strip and deposit the same as a course or layer in the formation of a wall” [9] [10] .The patents show a telescopic arm which rotates around a central point forming a wall layer by layer in a cylindrical shape,. It also supports a varying wall thickness, which is achieved by adjusting the mould at the end of the arm locally. Figure 3 and Figure 4, published in Everyday Science and Mechanics magazine in 1935, shows Urschel's vision of constructing spherical structures using this method. Aside from the clear lack of 3D model data, such a system is very similar to what we now call 3D concrete printing.



20 THRILLING WONDER STORIES

—the stuff they make houses and ships of nowadays—into this moving arm.

"It makes drawings in the air following drawings it scans with photo-cells. But plastic comes out of the end of the drawing arm and hardens as it comes. This thing will start at one end of a ship or a house and build it complete to the other end, following drawings only.

"It's ready to make a spaceship hull now. I need one. To power that ship I'm going to need three and possibly four mass time field units. One is to include the whole ship in its influence when it's turned on.

"Two others are to be set up along a tube fore and aft. They needn't be big. Come along and I'll show you the rough sketches, and you can plan them out, Thorn."

The big, white-haired man shook his head condescendingly.

"A mass time field isn't a space drive, Mr. Braddick," he said tolerantly. "I can do anything you say if Mr. Hamlin authorizes it, but—"

"He authorizes it," said Braddick. He looked at Hamlin.

"Oh, surely! Surely!" said Hamlin, beaming.

Braddick spoke gently:

"You're the trigger-man, aren't you, Hamlin?"

"Eh? What?"

"It's an obsolete term," said Braddick. "You're to see that I have an accident if I seem likely to do Atomic Power any harm, aren't you?"

Hamlin's mouth dropped open. He looked scared for a moment.

"Oh, don't worry!" Braddick told him. "I'm a sucker, this time—another obsolete term. I'm not a business man. There's some dangerous stuff coming this way, and I want to go out and meet it.

"My purpose is not to make profits, but to keep people from being killed. Quaint, eh? But I'm one of the people I don't want killed. Here's the drafting room."

He opened the door. The girl he called Jane was bent over the drafting board, making a working-drawing in three-colored inks with extraordinary pains to be accurate. She looked up, her eyes fearful. They flickered swiftly from one to the other of the men who represented Atomic Power. A vast relief seemed to fill her.

Then she turned back to her work. But Braddick saw Hamlin's face as he caught the first glimpse of Jane. Hamlin started and stared and an enormous inner excitement filled him. He fairly quivered, and his hand made an obscure movement, instantly checked.

"My assistant, Jane—er—Smith," said Braddick. "Thorn, look over those sketches. I've marked where I need the smaller time-mass fields. As I said, a field has also to enclose the whole ship.

"Give Miss Smith the outside dimensions of the apparatus you'll make to generate the fields and tell her where they'll have to be placed. She'll provide for them. Hamlin, come here a moment."

He led Hamlin through two doors.

"I'll take that flash-pistol, Hamlin," he said quietly. "In this pocket." He pointed to the pocket toward which Hamlin had made an arrested gesture on sight of Jane. "I wouldn't try to use it. Definitely not!"

Hamlin had had a shock. He had been terrifically excited. This was a new shock. Braddick took the flash-pistol.

"Who is she that you want to kill her the instant you see her? What's Atomic Power got against her?"

Hamlin protested vehemently. Braddick listened. Then he spoke.

"She's my assistant now, Hamlin. If you touch so much as her little finger, I'll kill you. You've run into somebody at work meeting an emergency. Don't make me use emergency methods on you!"

The first line of scouts—of which two had passed through the solar system—drove through space toward the Southern Cross. There was an infinitesimal resistance to their movement, caused by the one atom per cubic centimetre to be found in even the remotest part of interstellar emptiness, so the drive of the Things stayed on.

They needed to maintain their velocity. Their speed gave them mass. Their mass gave them invulnerability. An object with the mass of twelve suns will not be injured by collision with a meteorite or even an asteroid.

A plunge through a planet the size of Earth itself would hardly be noticed—but the planet would explode after the Thing had gone on.

There were thousands more Things on the way. After the scouts came the advance-guard. The main body was behind even that.

CHAPTER III

Treason!

JUST three men and a girl were at work to save the Earth. One of the men was quite useless, and one was condescendingly unbelieving, but he did make mass time units of the size and power Braddick dictated. The third man was Braddick, who got

Figure 3 Page 20 of Thrilling Wonder Stories (1945) **[8]**

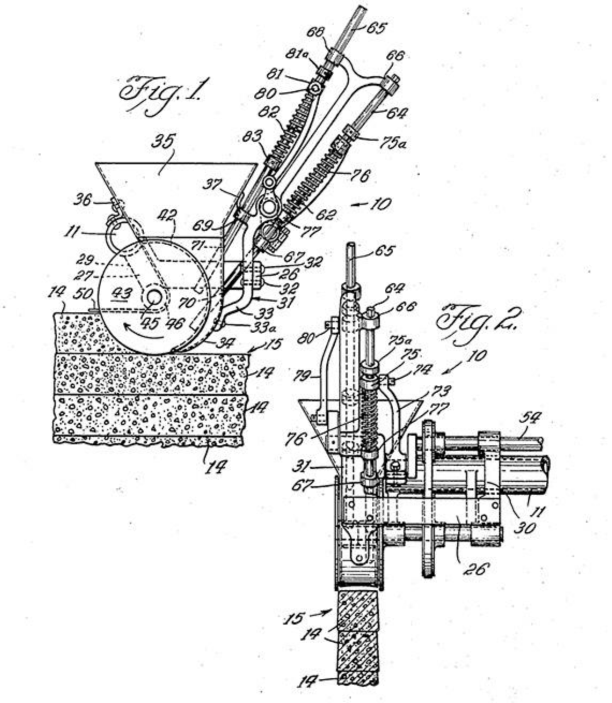


Figure 4 Urschel’s patent illustration **[9]**

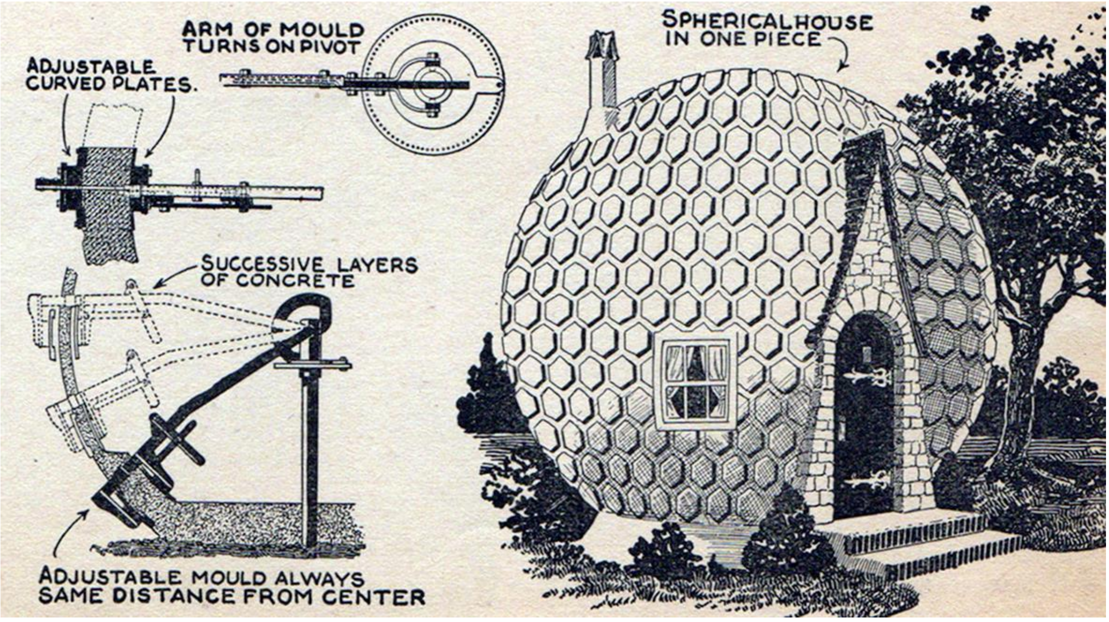


Figure 5 vision of constructing a spherical house **[10]**

Throughout the twentieth century, various patents were issued, including some by William Urschel's son Joe Urschel [11] [12]. The absence of (conventional) formwork and the layer-wise building of wall buildings are their common factors. The incorporation of fibres as a reinforcement strategy is described in the patents of Winn [13] and Goldsworthy & Hardesty [14].Multiple versions of the rotating telescopic arm can be seen in Figures 5,6,7 and 8. At the time, full automation of the process was not feasible; only mechanization was available. The geometrical possibilities of the manufacturing method dictate the shape of the cylindrical, spherical, or hemi-ellipsoidal structures illustrated in the patents. Although the geometrical freedom has been greatly expanded by the use of multi-axis robots, this relationship still holds today.

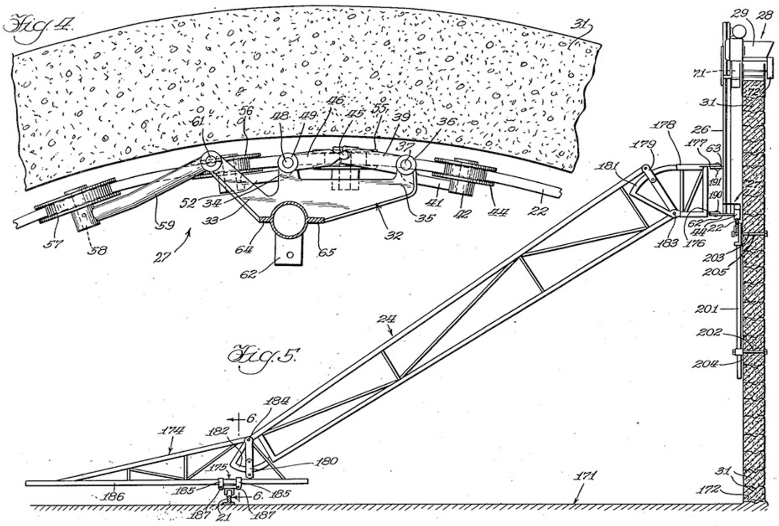


Figure 6 Urschel´s patent, 1952 **[15]**

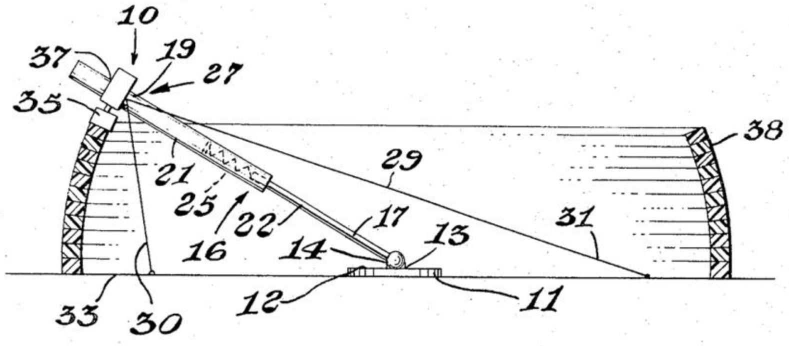


Figure 7 Lowes´ patent, 1968 **[16]**

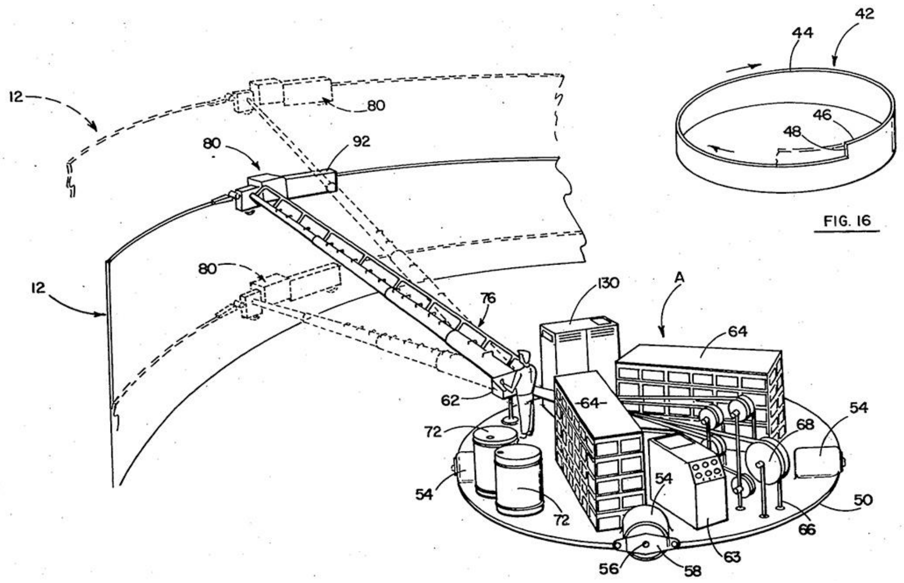


Figure 8 patent of Goldsworthy & Hardesty, 1976 **[17]**

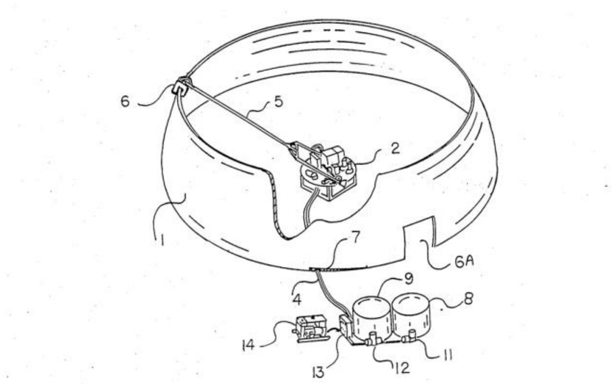


Figure 9 Maddock’s patent, 1988 **[18]**

In 1995, the first automated 3D concrete printing process was developed, which used a sliced geometry created with CAD software. Pegna begins a symposium contribution by saying, "This paper reports a radical departure from generally accepted concepts in construction automation and demonstrates that new techniques of layered manufacturing can be applied effectively to construction" while discussing a novel method known as Solid Freeform Construction. Pegna describes two approaches to ‘binder jetting' in this submission and a related journal publication, in which a reactive powder layer composed of sand and cement is locally injected and activated by water vapour. The procedure is then repeated by depositing a new layer of powder. The straightforward anisotropic behaviour due to the layer-wise manufacturing process [19] [20] was one of the observations, which is still an interesting research subject to this day.

Khoshnevis designed Contour Crafting (CC) at the University of Southern California in the early 1990s. CC is a 3D printing process based on extrusion that uses side trowels mounted on the nozzle to smooth the surface during printing. Initially, Khoshnevis printed small objects primarily with ceramic materials. The CC technique was scaled up at the beginning of the twenty-first century, and Khoshnevis created the famous printed wall structures, see Figure 9 and Figure 10, using a concrete mixture, which acted as an inspiration and baseline for many efforts in the following years. Two techniques are identified: one in which the printed concrete acts as a formwork and the inner space is filled with conventionally cast concrete, and the other in which the inner structure is also 3D printed, demonstrating a more effective material use unattainable by traditional casting techniques. In addition to those prototypes, Khoshnevis has designed automation ideas on the building site, such as automated reinforcement or CC plumbed incorporation, or multi-story building or tower printing, as well as various extra-terrestrial applications [21]. These notions have in advance shown the automation capabilities of the E&C industry, but have not yet found a way into practice.

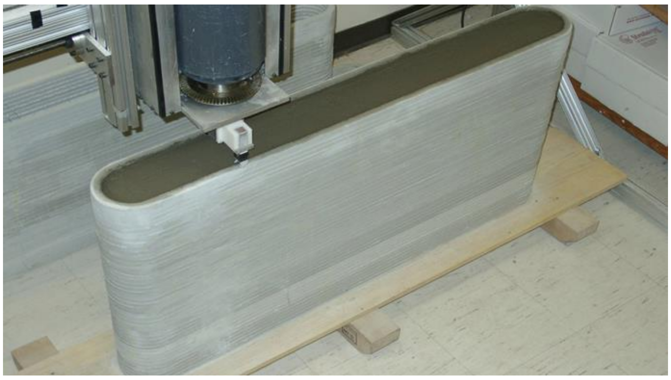


Figure 10 3D Concrete printed wall structures with conventionally cast **[22]**

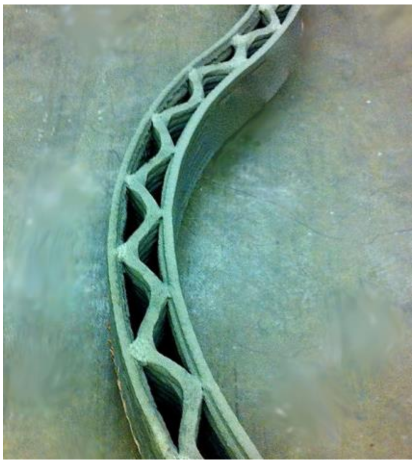


Figure 11 printed concrete infill, constructed by Contour Crafting technique **[23]**

The Italian engineer Dini created a method named D-Shape in roughly the same time. D-shape is a 3D particle bed printing process, which uses a cement-based particle mix similar to Pegna, unlike extirpation-based Contour Crafting. Dini has printed countless large-scale items since the founding of D-Shape in 2007. One of his first display objects, Radiolaria, shows the massive design freedom opportunities associated with 3D printing, see Figure 11. In 2017, ACCIONA, together with IAAC, produced a footbridge in Madrid with the help of a D-Shape printer in Figure 12. It is not certain if the printed components have a bearing function and how they are reinforced. However, the potential for creating aesthetic forms is impressive, as do all D-Shape objects.

Figure 12 Radiolaria constructed by a D-Shape 3D printer **[24]**

There have been several efforts in architecture and construction to investigate the possibilities of 3D printing. In 1997 the initial experiment on cement-based AM (additive manufacturing) took place. Concrete components are formed by the deposit of a thin layer of sand and the laying of a patterned layer of cement paste to adhere the sand selectively. The layers were compressed and steam is then used to ensure quick cure. However, the study has not been continued. In 1998, professor Berokh Khoshnevis developed the cementitious material additive manufacturing process called "Contour Crafting" at the University of Southern California [25], which later becomes an efficient way of printing residential buildings.

The Contour crafting builds concrete structures without using additional framework, by extruding cementitious concrete from gantry-driven nozzle layer by layer. In 2007, the large-scale powder-based 3D printer "D-shape" was designed by the Italian engineer, Enrico Dini

[26]. It aimed to build (sand with inorganic binder) based architecture artifacts with a depth of 5–10 mm per printed layer. The method is claimed to produce a substance with marble-like properties. A couple of years later, a robotic 3D printer called 'Stone Spray' was designed by Novikov et al. of the Institute of Advancing Architecture in Catalonia (Spain) in 2012 [27].It creates architectural structures by combining a sand or soil combination with environmentally-friendly binder. Following that, Platt et al. [28] developed (C-Fab) a cellular fabrication technology in 2013, which is more efficient and affordable than other large-scale 3D printing processes. C-Fab technology is used only for creating support structures for construction components.

Figure 13 Pedestrian bridge constructed by a D-Shape 3D printer **[24]**

First of all, insulation foam is sprayed inside the supporting structure then the lateral parts are sprayed with concrete material and additional exterior components such as bricks, stucco etc. are applied. Also, in 2014 a 3D printer with a scale of (12 m×12 m×12) m was unveiled by QingdaoUnique Technology. The printer extrudes a kind of half melt glass reinforced plastic material, layer by layer, on a base level, using technology similar to fused deposition modelling (FDM). to create the prototypes. In 2015, a new 3D printer called BigDelta, 12 m tall, 6 meters wide and with less than 100 W of power, was launched in the World Advanced Saving Project (WASP). On the open-air building site, Big Delta printed an adobe structure with eco-friendly components like clay, straw, soil and water. In order to have the materials, an elevator was attached to the printer scaffolding [29]

Chapter 3

Industrial adaptation and built examples

While additive manufacturing (AM) is still in its early life in the construction sector, it is clear that it has the ability to transform conventional building processes. At first, the adoption was at a glacial pace and the engineering and construction industry was not prepared for the change. Yet More and more of the manufacturing entities started following the lead of these original founders.

In recent years, automated buildings with 3D printing technologies have received growing interest as the building industry can actually be revolutionized with it and the idea of astronauts building on the moon started to look plausible [30]. It reduces building time and manpower significantly [31].

Since they lacked the necessary digital tools, the robotic leap of Pegna, Khoshnevis and Dini was not enough for their methods to be widely adopted even though they were able to take the works of Urschel and the others to another level.

During the first half of the twenty tens, the number of parties associated in 3D construction printing began to increase quickly, as true digitalization of the construction process became feasible, e.g. through the use of BIM, and was boosted by the rapid spreading of early results via social media.

A study by Wohlers [32] reveals that just 3 percent of the overall 3d printing market accounts for architectural applications. The sector is however early in its life, as its use for residential buildings only began in 2014 [33] and since then has shown tremendous promise.

In 2014 the global newspapers revealed that ten 3D printed houses were built in Shanghai in one day, as seen in Figure 14. These houses had been realized by Chinese company WinSun using their gantry-like 3D construction printer which measures approximately 150*10*6.6 meters.

Figure 14 3D Printed house **[34]**

With standard settings of related processes and the measurements of these structures, the declaration of time consumed is rather debatable and no specific information on the printing process has been published. WinSun uses an off-site solution, where simple components are printed, transferred to the construction site and then installed in a final structure to assemble the buildings mentioned. The 1-day statement may however concern the method of assembly and not so much the process of 3D printing.

The aesthetic quality of the printed buildings remains low and probably only a copy of the conventional (prefabricated) constructions and its performance has yet to be evaluated with regard to, for example, thermal comfort or energy consumption/efficiency. Also, since these houses are displayed near WinSun's 3D printing plant they are not inhabited by people.

Nevertheless, the production expenses and pace of printed buildings gained a worldwide interest in an era in which the demand for affordable housing hit an alarming level, illustrating 3Dconcrete printing opportunities for the wider public. This impact was amplified as WinSun released more exhibits over the years, including a multi-story apartment building and a villa (see Figure 15 and Figure 16), both of which were printed in a similar offsite printing manner.

Figure 15 3D printed multi-story apartment building **[34]**

Figure 16 3D printed villa **[34]**

The Contour Crafting technique was also introduced and scaled up at the same time, but on the other side of the world. Rudenko's company, "Complete Kustom," in Minnesota (USA), produced some of the first notable examples of on-site 3D construction printing.

First, a mini 3D printed castle was created in Rudenko's backyard in 2014; see Figure 17. The main body of the castle was printed on-site, however the top pieces were printed separately and then assembled [35]. Total Kustom was approached by an investor and the technique was sent to the Philippines after this early success and extensive media interest. Then in 2015, an entire hotel room (measuring 10.5×12.5×3 meters) was printed on site (Figure 18). It took over 100 hours for the printing process and the reinforcing bar and wiring were assembled manually [36].

Figure 17 3D printed castle **[35]**

Figure 18 3D printed hotel Room **[35]**

The technique of Contour Crafting – in more general, 3D extrusion-based concrete printing – has been successfully expanded by manufacturing companies, as shown by WinSun and Total Kustom, which is further demonstrated by the steady growing number of 3D printed buildings and dwellings presented in subsequent years.

For on-site 3D construction printing, CyBe (a Dutch 3DCP start-up) utilizes an industrial robot arm. As seen by recent showcases such as the R&Drone laboratory in Dubai in 2017, Figure 19 and a villa in Milan for design week in 2018, CyBe's 3D printers travelled around the world to realize many large-scale structures. The laboratory and villa are 168 m2 and 100 m2, respectively, and were printed in an effective period of 77 hours and 46 hours [37], demonstrating the ability of 3D construction printing to improve production speed.

Figure 19 3D printing by CyBe **[37]**

The Russian start-up Apis Cor has taken a similar approach, hoping to improve building efficiency by 3D printing directly on-site. With a remarkable similarity to the earliest examples of Urschel and others above, Apis Cor designed a custom 3D concrete printer and realized a showcase house in 2017, see Figure 20. The Danish 3D PrintHuset business, in the same year printed on-site the "Building on Demand", see Figure 21.

Figure 20 3D printing by Apis Cor **[38]**

Figure 21 3D printing by 3D PrintHuset **[39]**

The firm used a Spetsavia printer, showing that some companies have already targeted consumer market 3D-concrete printers. To showcase their equipment, Spetsavia created a 3D printed house in 2017 (see Figure 22), which was printed in parts off-site.

Figure 22 3D printing by Spetsavia **[40]**

In 2016, the Chinese company HuaShang Tengda 3D printed a two-story house directly on-site. This company employs a technique that involves placing a reinforcing mesh before printing. Concrete is then printed around and onto this mesh using a split nozzle. Figure 23

Figure 23 3D printing by HuaShang Tengda **[41]**

One of the key problems of 3DCP on site is to scale the device up to the appropriate size of the objects. This means that traditional 3D printers' sizes - mostly gantry systems- will have to expand several tens of meters to realize for instance multi-story buildings. However, scaling up 3D printers isn't the most effective solution, particularly for large structures.

Rather, on-site one or more mobile 3D printing robots can create a structure that would be much larger than them. This is shown, for example, by IAAC's project "Minibuilders" in Spain [42]. HuaShang Tengda gantry system for the 2016 home was successfully expanded and the castle-like, three story building printed on- site with a massive gantry system was revealed in 2018 by HuaShang Tengda, see Figure 23. However, it is unclear whether 3D construction printing still has an edge over conventional production methods with this size and printing resolution, because solid and orthogonal walls can be made easily using regular framework.

When efficiency rises, so cost reduction occurs, and as a result, projects have emerged to use 3D construction printing to provide low-cost housing for people in need, such as in third-world countries or disaster zones. In 2018, the start-up ICON collaborated with New Story to 3D print a house on-site in Austin, Texas, as seen in Figure 24.

Figure 24 3D printing by ICON **[43]**

In the same year, Be More 3D, a Spanish spin-off group, introduced their demo home, which was printed on-site (see Figure 25). While the Italian printing company WASP (World's Advanced Saving Project) has generally not used concrete but rather a mixture of earth-based and ceramic materials, since 2013 its aim has been to print 3D low-cost housing for people in need and recently has introduced one of the first 3D printed small homes, Gaia, see Figure 26.

Figure 25 3D printing by Be More 3D **[44]**

The ceramic 3D printed ‘cool brick,' for example, has an internal structure that enables air to move through walls and in order to cool the interior space [45]. This is an example of how not only the exterior geometry, but also the internal structure can be developed using 3D printing technology. Figure 27

The architecture company Emerging Objects introduced the ‘Bloom' structure, seen in Figure 28, using a cement-based powder bed printing method like D-Shape. It is made up of 840 3D printed blocks that have been custom made. Emerging Objects has printed several samples in order to show how this production technique can be used to implement additional features, in addition to highlighting the expressive architecture achieved by 3D printing.

Figure 26 3D printing by WASP **[46]**

Figure 27 cool brick **[45]**

Figure 28 3D Printed cement Bloom **[47]**

Figure 29 shows how the Thai company SCG demonstrated the use of the typical layered texture as an expressive element in a similar range of produced objects. The Dutch consortium of Bruil and Studio RAP uses off-site 3D construction printing to create customized facade panels, as seen in Figure 30, in order to achieve economical customization in architecture. Baumit, an Austrian company, has also introduced expressive 3D printed wall elements (see Figure 31). The scope for connecting digital parametric design tools to robotic manufacturing is evident in each of these cases. Pattern variability, print direction, and tessellation can all be easily created and produced.

Figure 29 3D printing by SCG **[48]**

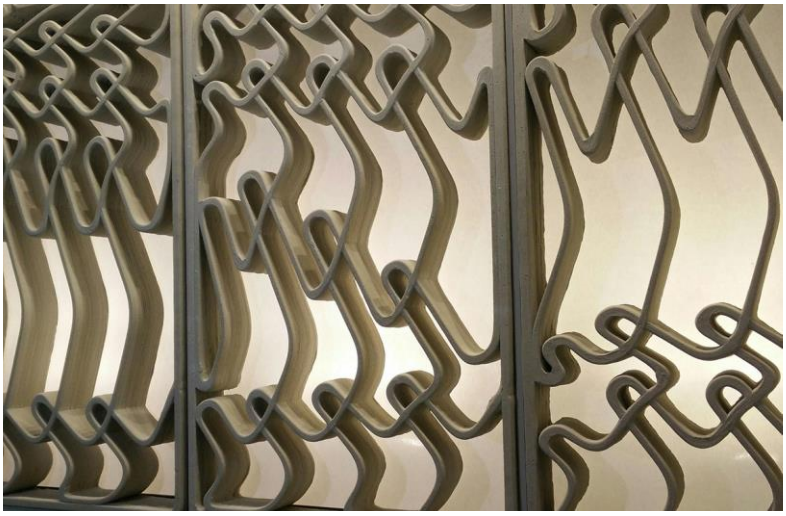


Figure 30 3D printing by Bruil & Studio Rap **[49]**

Another application has emerged in the underground infrastructure, due to the 3D construction printing process's suitability for achieving non-standard geometries. As seen in Figure 32, WinSun, XtreeE, CyBe, and Dubox have shown the use of 3D printing to create sewer pits, manholes, and storm water collectors, which have a highly position based, special geometry.

Finally, artificial reef systems are typically made up of complex geometries, and both WinSun and XtreeE have shown how 3D construction printing can be used in this area (see Figure 33 and Figure 34).

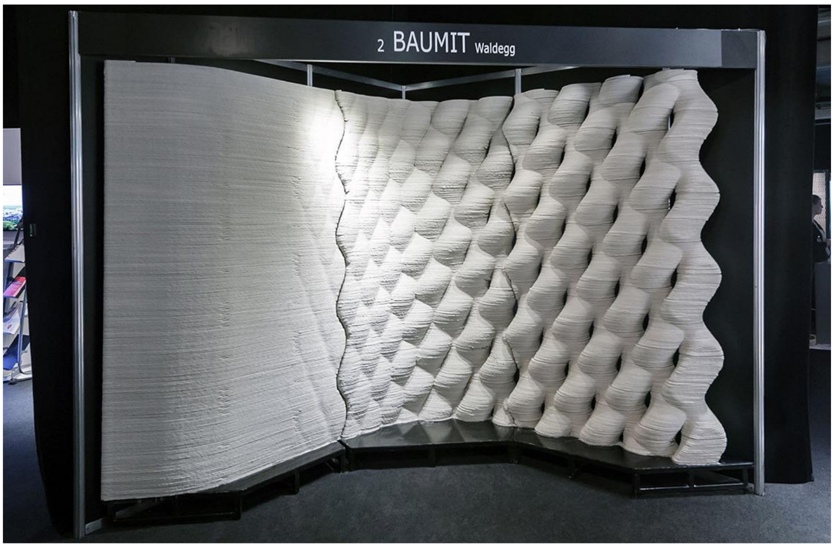


Figure 31 3D printing by Baumit **[50]**

Figure 32 3D printing by Dubox **[51]**

Figure 33 3D printing by WinSun **[34]**

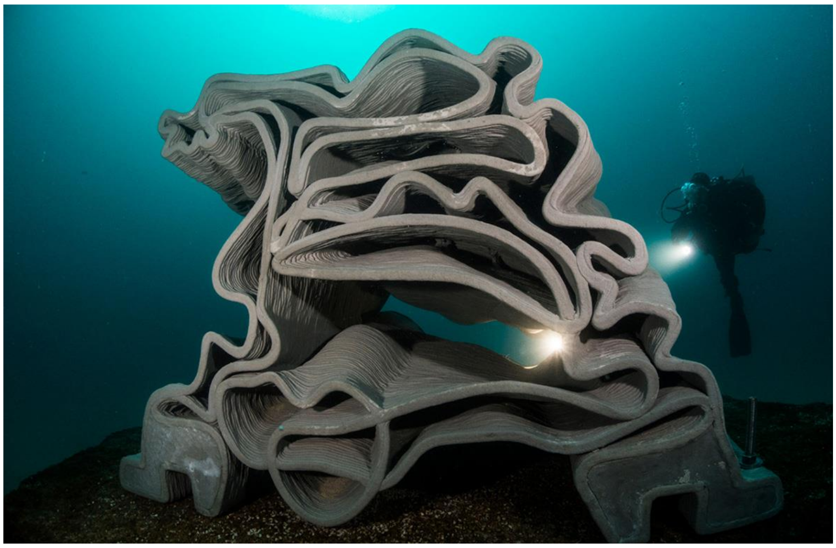


Figure 34 3D printing by XtreeE **[52]**

Most of the case studies mentioned show only some of the promise of 3D construction printing. They usually focus on 3D printing whole objects in one go on the location site, which promotes faster production, less workers, and lower costs as opposed to conventional manufacturing techniques. However, the structures produced by them do not differ much from those that other conventional techniques already achieve.

These results cannot recognize the potential of 3D concrete printing, in which additional complexity in design is achieved without added expenses expressed through increased aesthetic qualities or added functionality. However, this argument is specifically targeted by some companies as they focus primarily on the creation of elements that have high aesthetic quality, or additional functionality, in ways that are financially unreachable through traditional construction methods.

These elements are mostly made in off-site printing facilities and can then be shipped and installed on the construction field The French start-up XtreeE, for example, has demonstrated the freedom to use 3Dconcrete printing in design. Using the layered nature of the printing process, XtreeE introduces 3D printed items with reduced resource usage and improved expressive accuracy in a variety of case studies, ranging from urban furniture to pavilions (see Figure 35).

Figure 35 3D printing by XtreeE **[52]**

Following an initial phase of early pioneers such as Khoshnevis and Dini and other successors, the recent increase in industrial efforts has led to today's situation, where 3D construction printing has gained considerable traction worldwide. The fact that well-known parties in the Engineering and construction industry have recently implemented the approach emphasizes this point.

In 2014, for example, Skanska and Loughborough University formed a partnership [53]. Since 2016, LafargeHolcim has collaborated with XtreeE [54] and in 2017 Vinci Construction partnered with XtreeE [55], plus Doka Ventures started investing in Contour Crafting Corporation the same year [56].In addition, in 2017 [57], SIKA released a press conference revealing their 3D construction printing technique as well as a variety of showcase models (see Figure 36). Saint Gobain Weber Beamix and BAM Infra launched a commercial 3D construction printing facility in early 2019, targeted at producing anything from components to bridges and houses (see Figure 37).

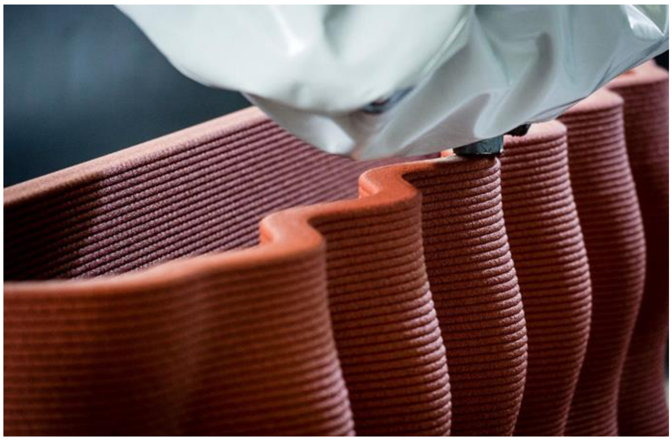


Figure 36 3D printing by SIKA **[58]**

Figure 37 3D printing by Weber Beamix & BAM **[59]**

In light of the current state of 3D construction printing, it is reasonable to presume that the printed structures created so far cover a wide variety of applications. Various institutes have also realized a 3D printed housing or small building using both off-site and on-site methods. The vast majority of these buildings, however, are uninhabited and function primarily as demonstrations of the 3D construction printing technique. In certain specific situations, where the buildings are still claimed to be inhabited, the 3D printed pieces usually obstruct an aesthetic feature or serve as a secondary load bearing structure to a main load bearing structure cast or applied within the printed components.

Figure 38, for example, shows how 3D construction printing is still in its early stage (lack of understanding of the structural behaviour of printed concrete, testing processes, and corresponding specification codes) limits the maximum potential use of 3D construction printing.

Figure 38 Primary load bearing structure applied inside of 3D printed elements **[34] [37] [39]**

The possible construction of lunar soil (regolith) based D-shape printing facilities on the Moon was evaluated. A theoretical design of the habitat has been created based on the outpost's design specifications.

The ability of the material to survive the lunar atmosphere is a critical feature of 3D printing. Labeaga-Martnez et al. [60] recently examined the use of AM in the European Space Agency's suggested Moon Village. The raw material for use with the various AM technologies which were evaluated was also Lunar regolith. Powder bed fusion was chosen as the best and most practical technique for the mission.

Mesh Moulding, a technique invented by Loughborough University, uses a six-axis robot to create elements without the need for temporary assistance. The mesh mould technique uses thermoplastic polymers, where the printed structure also reinforces the concrete. Once the concrete has been poured, it is trowelled manually to smooth the top. This technique is especially useful to build complicated structures, which can greatly reduce the production time required. Based on the forces that will affect the structure, the density of the printed mesh will differ. The inclusion of a steel mesh as reinforcement in the construction tends to increase the tensile strength of the concrete [7].

While Lim et al. [61]indicated that concrete printing is an off-site operation, they also claimed that with the right changes, on-site production processes could be achieved as a four-axis gantry and six-axis robot printers have been used for concrete 3D printing in recent years.

3D printing has now been an important tool in the preservation and reproduction of cultural artifacts. Xu et al. [62] devised a method for reproducing a historical structural part that combined 3D scanning with cement mortar-based 3D printing. When opposed to conventional approaches, this technology resulted in more cost-effective and labour-efficient construction.

Using strengths, weaknesses, opportunities and threats SWOT analysis to describe this technology, Sobotka and Pacewicz [63] investigated the various effects of using 3D printers on-site, especially in difficult environments. The researchers discovered that this technology would reduce the need for heavy machinery and building equipment while still allowing for the use of recycled materials. Stoof and Pickering [64] used recycled polypropylene (PP) to create a sustainable composite for fused deposition modelling FDM printing.

Since 3D printing uses different raw materials and production processes than traditional building techniques, the need for professional workers with the capability to combine robotic and civil work is still a challenge for AM in the construction industry [7].

One-third of the Earth's materials are thought to be used by the building industry. As a result, both material efficiency and effective design practices are critical for mitigating environmental effects. For 3D printing to be used to its full extent in a large-scale building project, it is essential to have a clear understanding of the technology.

With an increasing number of businesses demonstrating the promise of 3D construction printing, so do the expectations for this technology. However, once the excitement wears off, enthusiasm will wane unless the technique actually changes the traditional ways of the Engineering and construction industry sector. However, 3D construction printing has not yet matured to the point that it can meet the obstacles that lie ahead.

A broad range of technologies is necessary to cross the gap from the current state to the infrastructure required to actually change the E&C industry. 3DCP can only meet requirements if improvement is achieved in all areas, from material development and reinforcement techniques to safety measures and design concepts where the research sector comes into play.

Chapter 4
Main materials of 3D printing

Additive manufacturing is used in a variety of sectors including construction, prototyping and biomechanical engineering. Despite the benefits added from integrating 3D printing in the Engineering and Construction industry like reduced waste, freedom of design and automation, the technology was not ready yet and very limited and restricted.

In the world of 3D printing, Everyday a new material or a method for additive manufacturing is unveiled and new applications emerge with it. Also, recent advancements in manufacturing technology in general lowered the cost of 3D printers as the expiration of previous patents allowed manufacturers and gave them the opportunity to work on new 3D printing devices, this being one of the key driving elements for this technology making it more available.

Metals, polymers, ceramics and concrete including a variety of other materials are currently used in the additive manufacturing industry. 3D printed scaffolds are often made of ceramics, and concrete is the most common material used in construction additive manufacturing.

Since conventional processes are time-consuming, complex and expensive in the aerospace industry, advanced metals and alloys are commonly used. Also, the major polymers used in 3D printing of composites are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS).

The benefits of using a 3D printing system over conventional methods include the production of complex geometry with high accuracy, overall efficient management, product versatility, and customization. Yet, the mechanical properties and anisotropic behaviour of 3D printed pieces, on the other hand, limit the ability of large-scale printing. As a result, an optimised pattern of 3D priming is critical for controlling flaw sensitivity and anisotropic behaviour. Also, controlling the printing environment has an effect on the finished product quality [65].

One of the main difficulties to use this technique in a variety of fields is the limitation of materials available for 3d printing. Therefore, the development of appropriate materials for additive manufacturing is essential, also in order to improve the mechanical characteristics of 3D printed objects, continuous exploration is needed.

4.1. Metals and alloys

The development of metal additive manufacturing exhibits high growth. For instance, in 2016, the number of companies selling additive manufacturing Systems rose from 49 to 97, of which 49% of them were metal AM [32].

Compared to traditional production methods metal additive manufacturing allows a lot of freedom for the production of complex structures. Multi-functional elements can be designed and printed to solve structural, safety and insulation problems simultaneously.

This technology has primarily been used in the aerospace industry for testing, designing, and advanced applications [66]. It is also used in the biomedical, military and automobile sectors [32].

3D printing metals typically involves melting metallic material (powder or wire) with an energy source like a laser or an electron beam, then transforming the melted material layer by layer to form a solid component.

Direct energy deposition (DED) and Powder bed fusion (PBF) are the most widely used techniques for 3D printing metals, but also other techniques, such as binder jetting [67], cold spraying [68], friction stir welding [69], direct metal writing [70], and diode-based processes [71], have recently been introduced which can improve precision and speed.

PBF Technologies are able to produce high precision (±0,02 mm) components with good mechanical properties and complex forms. However, due to their slow speed (up to 105 cm3/h with four lasers), these systems are mostly used for small components.

PBF-based AM methods can be used to manufacture a variety of metallic materials, including stainless steels, some aluminium alloys, titanium and its alloys and nickel-based alloys.

Different types of lasers, such as femtosecond lasers, are now being studied [72]. Tungsten alloys and metals with high melt temperatures (> 3000 °C) and thermal conductivity (> 100 W/m·K) can be processed with these ultrafast lasers.

Advanced experiments are being performed to incorporate high-entropy alloys, magnetic alloys, bulk metallic glasses (amorphous metals), high-strength alloys, and functionally graded materials [73] as a result of study advancements in metallic materials and alloys for additive manufacturing.

Titanium and its alloys, nickel alloys, a few aluminium alloys, steel alloys and some cobalt-based and magnesium alloys have been optimised for AM [74]. In specific, titanium and its alloys are high-performance materials widely used in many applications [75], [76]. They are associated with high machining costs and a long lead-time based on traditional production methods. Thus, AM can deliver major economic benefits by manufacturing very complex structures at reduced prices and less waste. Ti [77] and Ti6Al4V [78] have been widely investigated and experimented on and are now being used for industrial applications in the aerospace and biomedical fields.

High-entropy alloys are made up of at least five principal metallic elements with atomic percentages ranging from 5% to 35% [79], [80]. As a result, a wide range of alloys with very different properties can be produced. These alloys have better strength-to-weight ratios, tensile strength, corrosion resistance, and oxidation resistance than standard alloys.

A variety of alloys are being used or tested for use or implementation of additive manufacturing. However, the vast majority of metal alloys used today (more than 5500) are incompatible with AM processes because the melting and solidification characteristics will result in microstructures that are unsuitable, such as columnar grains and periodic cracks [81].

A recent research by Martin et al. [82] shows that these problems can be solved by using nanoparticles that nucleates during additive manufacturing to regulate and control the solidification of alloys.

4.2. Ceramics

Additive manufacturing has been an important tool for producing advanced ceramics for biomaterials and tissue engineering, such as bone and tooth scaffolds [83]. The biggest obstacles for 3D printing of ceramics are layer-by-layer appearance and a small range of materials to use, despite the precision and accuracy of printing [84].

Sintered ceramic parts must be post-processed to achieve the desired shape, which is a time-consuming and expensive process. As a result, 3D printing complex shapes accompanied by sintering to create complex-shaped ceramics has become very appealing to manufacturers. Furthermore, by developing new innovative lightweight materials that are designed for diverse uses, 3D printing of porous ceramics or lattices has introduced various benefits. In comparison to conventional casting and sintering processes, ceramic scaffolds for tissue engineering have become faster and more convenient [83].

Inkjet (suspension), powder bed fusion, paste extrusion, and stereolithography are the most popular techniques for 3D printing ceramics. Inkjet is considered the most effective tool for producing dense ceramic samples that may not need post-treatment [84]. For 3D inkjet printing, a stable suspension with regulated controlled rheology that flows easily, does not clog at the nozzle, and dries effectively is a necessity [85].

3D printing also has the advantage of being able to manipulate the porosity of lattices [86]. Various techniques and materials have been studied in order to improve the mechanical properties of 3D printed ceramic lattices over conventional methods.

With the addition of CaSO4 and dextrin, Li et al. [87] formed a porous alumina ceramic with a high flexural strength. However, Maurath and Willenbacher [88] demonstrated that a high specific strength honeycomb structure could be produced without cracking and with better dimensional stability by improving the ink printing technique, both in terms of rheology and homogeneity of the ceramic suspension and optimization of sintering.

4.3. Concrete

In general, 3D construction printing hasn't been an easy field to experiment with, also the use of concrete as a printing material had its difficulties because of the material's behaviour during and after the printing process. To overcome these difficulties, many methods and mixtures have been developed in order to make the concrete an effective material to use in 3d printing.

The key aspects of effective contour crafting are fresh concrete properties. For 3D printing of complex forms, high early strength of concrete, such as buildability, and high workability for extrusion, such as extrude-ability or open time, are needed [89]. For a mix design which can meet the need for prolonged working-ability before setting for extrusion, a well-designed material and equipment are essential while maintaining high early strength in subsequent layers without structural collapsing and failure.

The rheological properties of the concrete mix, particularly the thixotropic behaviour, have been studied by Paul et al. [90] and found that it is an important factor that affects the pumping and printing of those mixtures.

A printing method that separates the accelerator and the premix mortar into separate tubes and then mixes them before extrusion in the printing head was developed by Gosselin et al. [91]. The rheology of the Premix Mortar can be regulated for a longer period of time without sacrificing the early strength of the printed layers, allowing the next layers to be effectively created. With a six-axis robotic arm, this device can build larger structures and track the material behaviour before or after extrusion, achieving complicated geometries with no temporary assistance.

In order to maximize the building rate without fracturing or deformation of the underlying layer, Perrot et al. [92] have developed a theoretical framework focused on the rheological behaviour of cement mixtures. Also, a high-performing 3D printed polypropylene fibre-reinforced mortar compromise of Portland cement, fly ash, silica fume and sand (aggregate size limit of 2 mm) has been developed by Le et al. [89]. Extrusion with a 9mm diameter nozzle drum over a span of 100 minutes of open time was possible with the use of superplasticizers and retarder. The resulting mixture can be constructed up to 61 layers thick (about 400 mm).

The advantages of managing fiber orientation with 3D printed concrete when compared to conventional fiber-reinforced concrete shows that flexural strength improved dramatically by as much as 30 MPa for the free oriented carbon fibres along different printing paths in the case of printing parallel lines in the x-y plane [92].

Zhong et al. [93] studied an alkaline-activated (3D printed nanocomposite geopolymer) Portland cement-free concrete. The geopolymer system's nanographene oxide has led to appropriate rheological properties for extrusion, increased compressive strength of approximately 30 MPa and increased electrical conductivity. In order to print in a finer resolution, a mixture of quick hardening cement and polyvinyl alcohol (PVA) was used. However, delamination of the layers and void forming between the layers were observed, which were less distinctive after the samples were cured in water, [94].

The mix design of a cementitious mortar, with OPC and Sulfoaluminum Cement (SAC), was investigated by Zhu et al. [95]. The major difference between both materials is setting time; SAC has a fast setting time and high early strength, but OPC has a long setting time and a slow hydration. Following examination of all these materials, SAC has been suggested for its properties to be a more suitable material for 3D print mortar because early setting time is considered necessary for 3D printing since lower printed layers need to have enough strength to support the top layers.

The printing parameters, such as the nozzle type and shape, regulate the mechanical properties of samples which are controlled by the printing directions, Paul et al. [90] explained. The effects of aggregate size, extrusion and layer thickness on the bond strength between the layers were studied in Zareyan and Khoshnevis [96] since the adhesion of the interlayers is one of the major 3D printed structural problems. A 3d printed concrete structure done by them is seen in Fig. 5. Due to stronger interlayer bonding, they observed that the smaller maximum aggregate size and more cement to aggregate content produced a higher strength.

Despite the better interlayer connection and bonding, the increasing thickness of the layers with more periods of time between the following layers decreased the compressive strength of the printed structures. On the other hand, the probability of cold joints between layers may be increased by a shorter setting time [96].

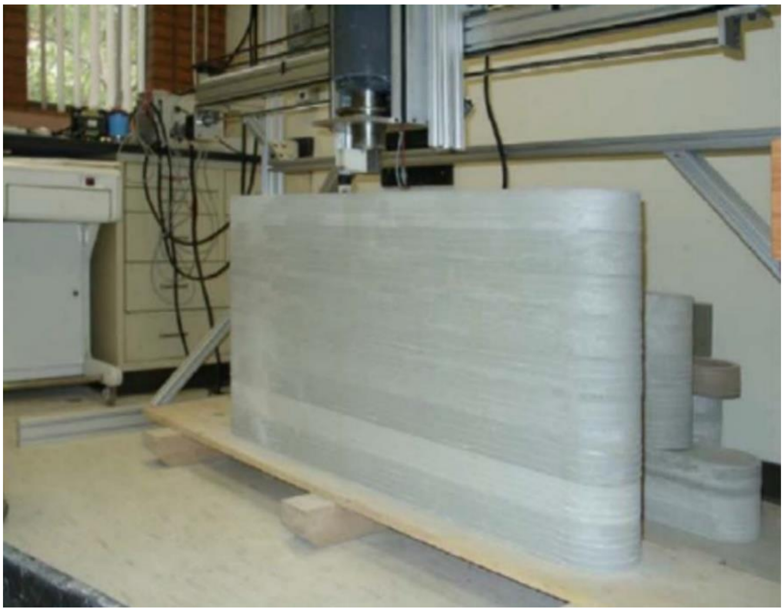


Figure 39 3D printed concrete structure (courtesy of Zareiyan and Khoshnevis) [96]

The stability and resistance of printed layers against collapsing and deformation induced by subsequent layer printing define shape-stability of the printed element. Kazemian et al. [97] demonstrated significant improvement of the 3D printed cement paste's shape-stability by adding silica fume and nano-clay. The other key problem for complex and large 3D printed structures is the lack of adequate external support and its removal process After the construction process ends [98].

The process of powder bed fusion was studied despite the main emphasis on 3D printing of cement and concrete paste. The powder bed was made of a mix of ordinary Portland cement and calcium aluminate cement, with an aqueous solution of lithium carbonate as the binder, according to Shakor et al. [99]. Considerably high porosity of approximately 50 percent, about 8 MPa of compressive strength and low hydrating levels were observed due to minimal and limited powder-water interaction.

Xia and Sanjayan [100] experimented with a 3D printed powder structure in a geopolymer system. The powder bed is made of ground blast furnace slag, sand and ground anhydrous sodium silicate (alkali activator), with a liquid binding agent which consists of water and a small amount of 2-Pyrrolidone. The 3D printed cubic test specimens have dimensional expansion of less than 4% with a very low strength of 0.9 MPa. The strength up to 16.5 MPa improved after treatment of the samples with an alkaline solution at 60°C. In full-scale 3D printed structures however, the treatment of the alkali solution and high temperatures is considered implausible.

3D printing wet concrete has many challenges and they are not limited to the management of the fresh properties of concrete in order to provide adequate workability and open-time for extrusion but also to structural features such as strength, adhesion between the layers, deformation, build-ability and durability of 3D printed structures. For example, since there is no framework to protect against air exposure relative to regular concrete, the 3D printed structure may have an accelerated water evaporation which raises the shrinking and cracking chance.

4.4. Comparison of different materials for 3D printing

Table 1 A summary of main applications, benefits and challenges of the main materials for additive manufacturing **[101]**

Materials	Main applications	Benefits	Challenges
Metals and alloys	Aerospace and Automotive Military Biomedical	Multifunctional optimisation Mass-customisation Reduced material wage Fewer assembly components Possibility to repair damaged or worn metal parts	Limited selection of alloys Dimensional inaccuracy and poor surface finish Post-processing may be required (machining, heat treatment or chemical etching)
Polymers and composites	Aerospace and Automotive Sports Medical Architecture Toys Biomedical	Fast prototyping Cost-effective Complex structures Mass-customisation	Weak mechanical properties Limited selection of polymers and reinforcements Anisotropic mechanical properties (especially in fibre-reinforced composites)
Ceramics	Biomedical Aerospace and Automotive Chemical industries	Controlling porosity of lattices Printing complex structures and scaffolds for human body organs Reduced fabrication time A better control on composition and microstructure Mass-customisation	Limited selection of 3D-printable ceramics Dimensional inaccuracy and poor surface finish Post-processing (e.g. sintering) may be required
Concrete	Infrastructure and Construction	No need for formwork Less labour required especially useful in harsh environment and for space construction	Layer-by-layer appearance Anisotropic mechanical properties Poor inter-layer adhesion Difficulties in upscaling to larger buildings Limited number of printing methods and tailored concrete mixture design

Chapter 5

Design methodologies of cementitious materials for 3D printing in construction

The general principle indicates that the cementitious content must be optimized to comply with the design of the 3D printer, including its material storage system, delivery system, depositing system, printing system, and control system, in order to ensure a mixture of sufficient workability and printable and reliable performance for use in a large scale 3D construction concrete printer [102] and in order to achieve a continuous paste from the printing nozzle which ensures quick and rapid modelling of freeform structure, the cementitious material must be easy-extrusive, easy-flowing, well-buildable, and has good mechanical strength and proper setting time.

An overall criterion for mixing design of cementitious mixture for 3D printing on the construction scale is shown in Figure 40.

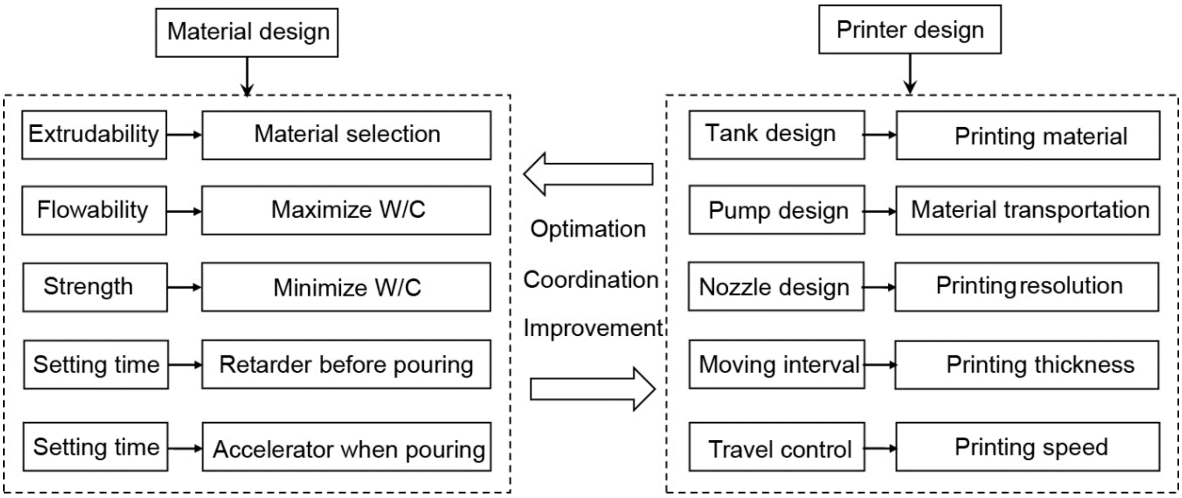


Figure 40 General requirements in the mix design of cementitious mixture for construction-scale 3D printing **[103]**

5.1. Extrudability control

The cementitious materials for 3D printing require an appropriate level of extrudability, linked to the material's capacity to flow continuously through the narrow pipes and nozzles on the printing head. A smooth grading of materials is needed for extrudability control of cementitious materials for 3D printing and alternative raw materials should have fine particles and a rounded shape.

In order to determine the best extrudability control for cementitious materials a number of experiments have been conducted. According to Malaeb et al. [104], the best mixture had a fine aggregate to cement ratio of 1.28 and a fine aggregate to sand ratio of 2.0 and the maximum size of an aggregate is 1/10 of the printing nozzle diameter.

Perrot et al. [92] developed a cement paste with 50 percent cement, 25 percent limestone filler, and 25 percent kaolin for use in 3D printing extrusion methods. All three powders have average particle sizes of 10, 9 and 15 µm.

To make concrete paste for a narrow nozzle with a diameter of 9 mm, Le et al. [89] chose sand with a maximum particle size of 2 mm. The ideal mixture of a high-performing printing concrete mixture was discovered to be a 3:2 sand-binder ratio with the latter comprising 70 percent cement, 20 percent fly ash and 10 percent silica fume.

Using circular shape aggregates instead of angular aggregates would allow for greater extrudability control and reduced blocking risk for a given water to powder ratio. A considerable amount of cementitious material paste must be used to fill the voids created between smooth graded aggregate particles which is the general concept for grading design of the printing material. This is somewhat close to the process preparation of self-compacting concrete [105] [106].

5.2. Flowability control

In general, many interrelated aspects affect the flowability of cementitious material and to ensure achieving desirable flowability a properly defined formula is needed, as controlling flowability ensures that the paste is easy to deposit and easy to pump in the deposition and delivery systems.

To increase the flowability of cement mixtures, there are two typical methods: the water to binding material ratio and the particle grading of concrete paste.

Water to binder ratio (W/B) is obviously the most significant factor concerning cement paste flowability. A higher water content, on the other hand, could result in a large pore or void content and lowering of mechanical strength significantly [107].

In certain situations, a superplasticizer is used to increase cement paste flowability while retaining equal or higher mechanical strength, as water content rises the superplasticizer will scatter the flocculated cement particles, releasing some of the water contained within the voids and improving the paste's rheology fluidity [108] [109].

Le et al. [89] showed that a concrete mixture with a water binder ratio of 0.26 and a superplasticizer binder ratio of 0.01 can be printed up to 61 layers in one session using a 9 mm diameter nozzle and consistent filaments.

Malaeb et al. [104] used a slump flow test to assess the flowability of 3D printing concrete materials containing four mass ratios of superplasticizer. Concrete materials of 0.14 percent, 0.28 percent, 0.3 percent, and 0.35 percent superplasticizer had flowability values of 1.1, 1.15, 1.2, and 1.4 cm/s, respectively.

The other major element that determines the rheology and fluidity in the fresh state of the concrete paste is its particle grading. In general, a wider particle size distribution will help to improve the packaging density and flowability of the concrete paste [110] [111].

The powder content and the coarse aggregate content should therefore be adjusted to achieve the maximum packing density.

Fine mineral admixtures such as fly ash, blast furnace slag, and silica fume (through proper mix proportioning) fill the voids created between larger cement particles, act as a lubricant to prevent cement particles from turning into blocks and slow the hydration of cement, thus displacing the water in the voids and improving paste flowability [112]. Yet, having excess fine powder content can increase the paste's viscosity, resulting in a negative effect [113].

Ferraris et al. [114] explained that the maximum viscosity of 0.06 Pa s of cement paste was observed to be around a mean particle diameter of about of 11 mm and at a mean particle diameter of 5.7 mm a maximum yield stress 30 Pa was reached, Ferraris et al. [114] .

5.3. Buildability control

Another important factor to recognize when evaluating the printable quality of cementitious materials is its buildability, which translates into the material's ability to maintain its extruded shape under self-weight and pressure from upper layers, which can be thought of as early stage stiffness.

Sufficient buildability is required for the extruded cementitious paste which means it should maintain the shape right after the deposition, could be laid down accurately, be able to withstand the weight of additional layers without collapsing and at the same time it must be suitable for providing enough bond between layers.

Small quantities of a viscosity modifying agent (VMA) may be added to concrete mortars to reduce bleeding and increase durability. The VMA also reduces the powder requirement while achieving the necessary stability.

Sonebi et al. [115] discovered that when VMA was fixed at 0.06%, plastic viscosity value decreased from 2.18 Pa s to 1.6 Pa s with the increase of amounts of superplasticizer from 0.6 percent to 1.1 percent.

Lachemi et al. [116] found that when the shear rate is set to 10 s-1 the apparent viscosity of paste with 0.075 percent viscosity modifying agent (VMA) was more than four times greater than that of paste with 0.025 percent VMA.

With the rise of VMA dosages from 0.025 percent to 0.075 percent, yield stress was reduced from 18 Pa to 4 Pa.

Early strength agents may promote hydration and reduce the setting time of cement.

Lin et al. [117] examined the effects of three types of early strength agents on the strength of cement-based printing material: lithium carbonate, lithium hydroxide and sulphates. The findings of the tests show that a ratio of 0.05 percent lithium hydroxide will reduce setting time to 9 minutes, and that cement mixed with lithium hydroxide has the highest improvement of 2-hour strength.

5.4. Setting time control

Printing material needs a long setting time to maintain constant flow rate for decent extrudability where appropriate retarders can be used to regulate setting time as on the surface of cement particles the retarders can be absorbed to create a layer which is insoluble and delays cement hydration.

Lin et al. [117] evaluated the effect on the setting time of extrudable printing material of six common retarders. The best retarder of the cement-based paste was sodium tetraborate, which could increase the jelling time from 28 minutes to 109 minutes and the final setting time from 49 min to 148 min when its mix ratio is from 0.1 percent to 0.3 percent.

Printable material, in general, needs a short setting time to achieve sufficient early strength after being deposited from nozzles.

Accelerating admixtures are chemicals that speed up the hydration of cement, reducing the time it takes to set and improving the speed at which early stiffness develops.

The setting time of cementitious mixtures mixed with different accelerators was studied by Paglia et al. [118] and found out that the setting time of concrete with a 4.5 percent mass dose of alkaline accelerators was around 57 percent of that with an 8.0 percent mass dose of alkaline-free accelerators.

According to Maltese et al. [119], a dose of alkali-free accelerator ranging from 2.0 percent to 7.0 percent by cement mass reduces the setting time of cement paste from 360 minutes to 150 minutes.

5.5. Mechanical property control

During the last years, many experiments have been done in order to improve the mechanical properties of the printed objects.

Gosselin et al. [91] proposed a new high-performance printing concrete paste premix consisting of 30 wt%–40 wt% Portland cement, 40 wt%–50 wt% crystalline silica, 10 wt% silica fume, and 10 wt% limestone filler(wt: weight percent). The printed samples have flexural strengths ranging from 11.7 MPa to 16.9 MPa.

Nerella et al. [120] used 31.1 percent brick, 22.3 percent limestone, 18.2 percent aerated concrete, and 3.7 percent lightweight concrete to provide a potentially replaceable material for concrete 3D printing. Also, according to Shao et al. [121] extruded fiber composite outperformed casted products in terms of strength, stiffness, fiber distribution, and orientation.

The mechanical behaviour of 3D printed structures using cement powder is analysed by Feng et al. [122]. The average compressive strength of printed cubic specimens varies between 7.23 and 16.8 MPa, making them unsuitable for structural use.

Lim et al. [61] produced a high-performance cementitious mixture for concrete printing that contains 54% sand, 36% reactive cementitious compounds, and 10% water with water-to-binder ratio around 0.28. Extruded and deposited paste compressive strengths range from 80 percentage to 100 percent to those of a typical cast specimen. Extruded samples' flexural strength is close to that of a normal cast specimen.

Christ et al. [123] used a matrix of cellulose-modified gypsum powder and incorporated 1% short PAN fibers with a maximum length of 1 cm. As compared to non-reinforced samples, printed samples showed a 180 percent improvement in bending strength and up to ten times higher fracturing strength. Using longer length of fibers with higher content further increased flexural strength to more than 400% but the composite was rendered unprintable.

Nerella et al. [124] introduced a high-performance printable mortar formulation. All of the values measured (regarding compressive and flexural strength) were greater than those seen in typically cast specimens. Saw-cut specimens had compressive strengths of 80.6 and 83.5 MPa in perpendicular and parallel directions to the layer-interface plane respectively. Also, Flexural strength were 5.9 MPa and 5.8 MPa respectively.

Using 1.2 kg/m3 micro polypropylene fibers as an added element to the concrete mixture, Le et al. [89] introduced a high-performance printing concrete. This material had compressive strengths of 20, 80, and 110 MPa at 1 day, 7 days and 28 days, respectively.

Feng et al. [122] introduced new complex structures made up of 3D printed components reinforced with FRP materials, 3d printed samples covered in FRP sheets had a peak compressive strength of 31.5 MPa, 1792.0 percent over the unreinforced samples.

5.6. Shrinkage control

Shrinkage is a big issue associated with cementitious material printing performance because it impacts the stability and dimensional accuracy of printed structures as the dimensions of the printed element would decrease with the passage of time from the initial measurement.

Significant drying shrinkage deformation happens during the composite's setting and hardening phase since the remaining water evaporates from the cement [125].

Compared to regular casted structures that use formworks, 3D printed parts often have a greater surface area directly exposed to ambient conditions which would promote the evaporation of free water [126].

In general, 3D printing cementitious material needs a high content of water to have sufficient flowability and extrudability so excess water is applied above the needed amount for hydration and as part of this particular requirement, shrinkage control is very important.

Shrinkage can be regulated by lowering the water to cement ratio (W/C) or increasing the sand to cement ratio (S/C) as there are a variety of ways to avoid shrinkage.

For a given age, the drying shrinkage strain can be reduced by a low W/C value, also the finer the aggregate is, the less the composite experience shrinkage deformation [127].

When fly ash and calcium sulfoaluminate cement are used together, shrinkage under drying conditions is reduced by over 80% [128] so SRA (shrinkage mitigating admixture) is often used to minimize shrinkage by decreasing the surface tension caused by water evaporating.

Another shrinkage control technique is the addition of fibers which it could also reduce and control the shrinkage crack to a manageable amount. When compared to concrete without any mixing fibers, experimental test findings show that the crack area in the mix with structural nano-synthetic fiber (0.26 vol%) decreased by 36.0 percent [125].

5.7. Optimization for mixture proportion

The cementitious materials mix for the 3d construction printing purpose must be well optimized in order to satisfy the fresh and hardened material specifications. Figure 41 shows a chart detailing the cementitious mixture design and preparation process for construction-scale 3D printing.

To ensure the mixture can be smoothly deposited from the printing nozzle, extrudability should be the first aspect to be thought of and that is by choosing grading raw materials with a maximum particle size of 1/10 the diameter of the nozzle. Also, the water to binder ratio (W/B) should be adjusted to make the mixture provide an optimal flowability that allows the material to flow freely into the delivery system.

We should always take into consideration that the quality of the printing process is controlled by the material behaviour at the fresh stage. After the raw materials and water-to-binder ratio have been determined, the mixture can be tweaked to enhance and manage the buildability, setting time, strength and shrinkage control by using additives like superplasticizer, pozzolanic particles, retarder, fibers and accelerator...etc.

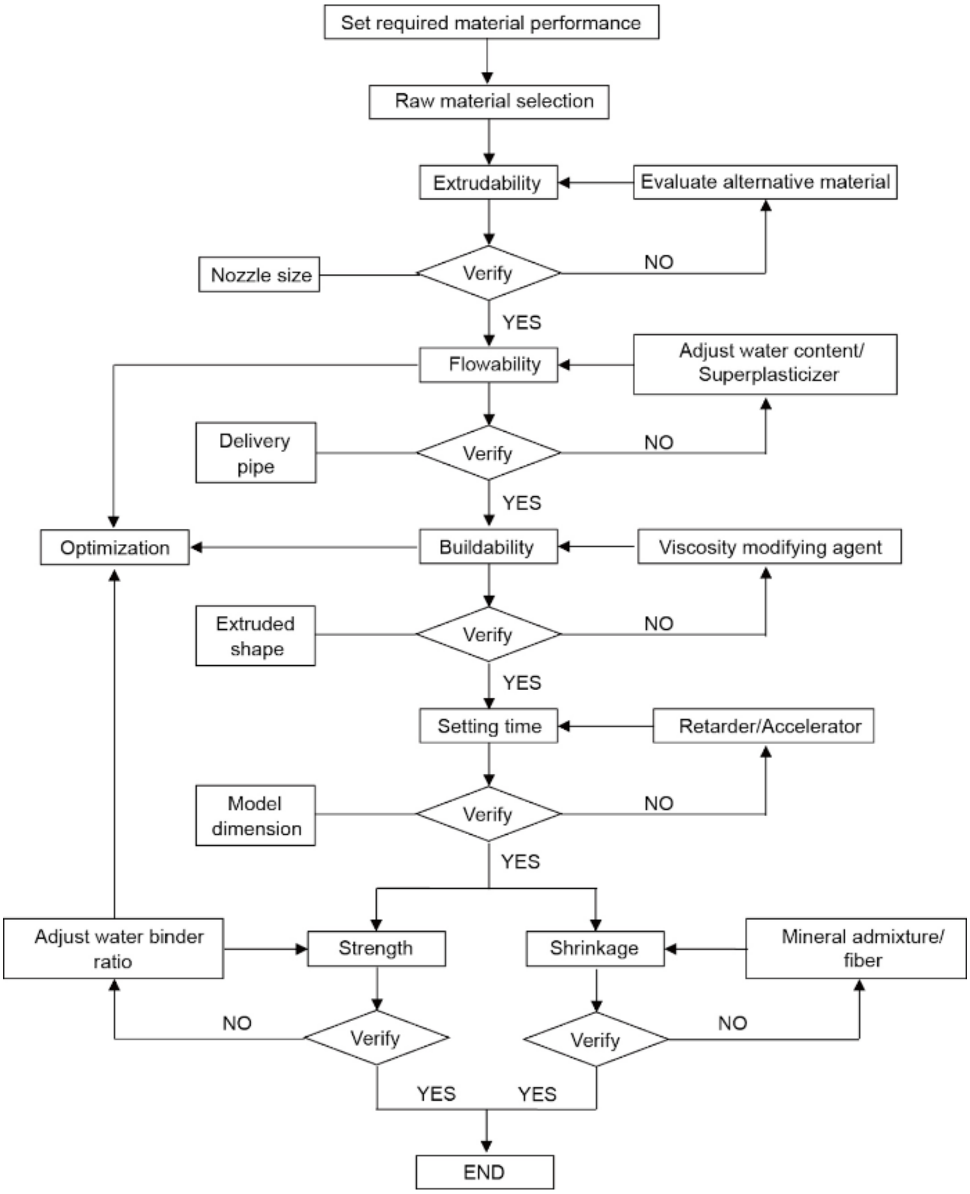


Figure 41 Preparation procedure for cementitious mixture design for construction-scale 3D printing. **[103]**

However, in terms of flowability, buildability, and mechanical strength, there are multiple issues in the mix phase like the water to binder ratio (W/B). As mentioned above, cementitious paste needs a large amount of water to be delivered smoothly. However, cementitious paste must have a low water to binder ratio to achieve reasonable buildability (i.e., the ability to retain extruded shape)

Another issue arises as a result of the setting time. On one hand, decent flowability necessitates a relatively long setting time in order to sustain a constant flow rate and avoid system blocking. Good buildability, on the other hand, necessitates a short setting time to enable the material to harden quickly enough to support the weight of subsequent layers.

To overcome these issues, superplasticizer is used to balance the water to binder ratio (W/B), while retarder and accelerator are used to regulate the setting time of cementitious paste in both the fresh and hardened states.

Chapter 6

Main procedures (methods) of 3D printing in construction

6.1. General methods in 3D printing

Additive manufacturing (AM) has been in development for decades now and new methods everyday are being introduced in order to meet the needs for printing complex forms and structures. A few of the main factors that influence the growth of additive manufacturing technologies are improvement of mechanical properties, the ability to print large structures, rapid prototyping and the reduction printing defects.

There are many methods for additive manufacturing (AM) like selective laser sintering (SLS), selective laser melting (SLM), liquid binding in three-dimensional printing (3DP), fused deposition modelling (FDM), contour crafting, stereolithography, laminated object manufacturing (LOM) and direct energy deposition (DED), these methods uses different materials and equipment depending on the application.

Bhushan and Caspers [129] did a detailed analysis of these approaches, also Mao et al. [130] explored novel methods for specific applications like projection micro stereolithography (PμSLA) and photon polymerization (TPP).

6.1.1. Inkjet printing:

Inkjet printing is one of the fastest and efficient technologies for additive manufacturing of ceramics, allowing for freedom in designing and printing complex structures. It is used for printing specialized and advanced ceramic structures for applications such as scaffolds for tissue engineering.

A stable ceramic suspension is pumped and deposited in the form of droplets onto the substrate through the injection nozzle then the droplets solidify creating a continuous pattern that is strong enough to retain additional layers of printed materials Figure 42.

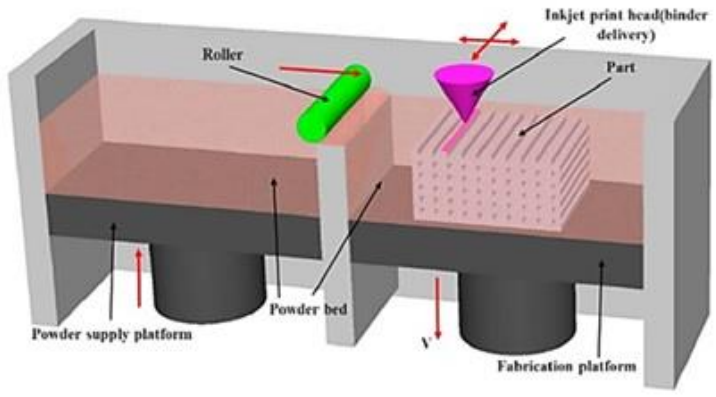


Figure 42 Schematic diagram of inkjet printing **[131]**

Wax-based inks and liquid suspensions are the two major categories of ceramic printing materials. To solidify wax-based inks, they are melted and deposited on a cold substrate. Liquid suspensions, on the other hand, are solidified by liquid evaporation.

The output quality of inkjet-printed components is determined by ceramic particle size distribution, ink viscosity, nozzle size, extrusion rate and printing speed [132].

The major disadvantages of this approach are its poor resolution, lack of adhesion between subsequent layers and low workability.

6.1.2. Powder bed fusion:

Powder bed fusion (PBF) is an AM method that uses thin layers of spread out extremely fine powders which are closely packed on a base, then a laser beam or a binder is used to fuse the powders in each layer together, powder layers are rolled over the previous layers and fused together until the final form is created Figure 43. A vacuum is used to collect the residual powder. At this stage, any processing and detailing is carried out.

The most important aspects in the effectiveness of this approach are powder size distribution and packing, which define the density of the printed component [133]. Only powders with a low melting/sintering temperature can be used with the laser; otherwise, a liquid binder is used.

Selective laser sintering (SLS) can be used on a wide range of plastics, polymers and alloy powders, whereas selective laser melting (SLM) is limited to metals like aluminium and steel.

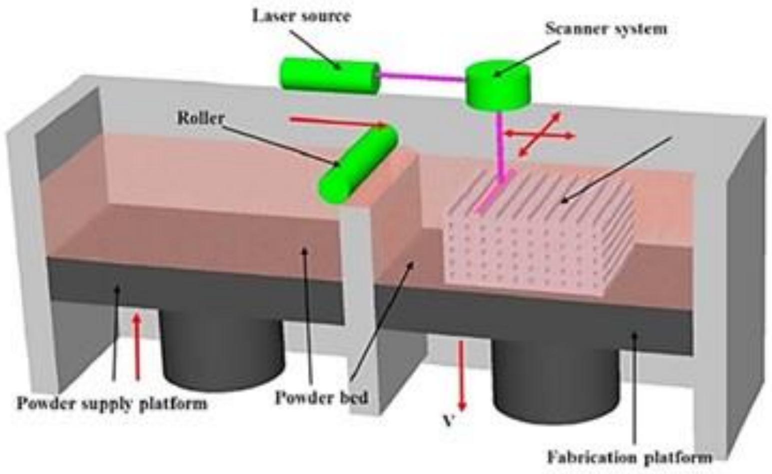


Figure 43 Schematic diagram of Powder bed fusion **[131]**

Selective laser sintering (SLS) method uses laser scanning to fuse the powders at the molecular level by elevating local temperature on the surface of the grains without fully melting the powders. However, selective laser melting (SLM) method results in superior mechanical properties since it fully melts and fuses the powders together [134].

Three-dimensional printing or 3DP refers to the process which uses liquid binder, there are many key aspects to consider while using 3DP like size and shape of powder particles, the chemistry and rheology of the binder, deposition speed, the interaction between the powder and binder and post-processing techniques play an important role in 3DP [131] [133].

As compared to laser sintering or melting, which can print dense components, the porosity of components printed by binder deposition is usually higher [133].

The key parameters influencing the sintering process are laser power and scanning speed.

Lee et al. [134] provide more information on various types of lasers and their effect on 3D printing.

Powder bed fusion's key features are good resolution and high printing quality, making it ideal for printing complex forms.

This process is used in tissue engineering, aerospace, electronics and in many other innovative and complex industries.

The biggest benefit of this approach is that it uses the powder bed as a support, which eliminates the troubles of removing supporting material. On the other hand, high costs, slow processing time and high porosity (in case of using a binder) are the main drawbacks of this method.

6.2. 3D printing in construction field

The investment in development of the construction field has always been a priority for a lot of scientific fields since built environment and infrastructure are the backbone of any civilization and for that, 3D printing technology is not an exception as large-scale additive manufacturing has been modified to meet the needs of the design and construction industries.

6.2.1. Contour crafting

Contour crafting is a process similar to inkjet printing and it is the main 3D printing method related to constructing large scale buildings, it uses an automated process to produce planar and freeform surfaces accurately and it provides high level of surface quality, fast construction time and a large selection of optional materials.

Using this method, the structural components can be made up quickly by choosing materials with low shrinkage and fast curing properties.

To produce smooth and precise object surfaces, two trowels are mounted on the printing nozzle. the printing nozzle travels along a predetermined path to print the exterior sides firstly. Then, to fill the internal volume created by the outer edges, another kind of cementitious material is poured [100].

Contour crafting was created to solve the problem of high-speed automatic design [135] [136] since it uses a multi-axis robotic arm to print massive structures with dimensions of several meters.

The printing nozzle can travel along the X and Z axes with the help of a gantry mechanism, and the nozzle can move along the Y axis with the help of two parallel sliding structures as seen in Figure 44.

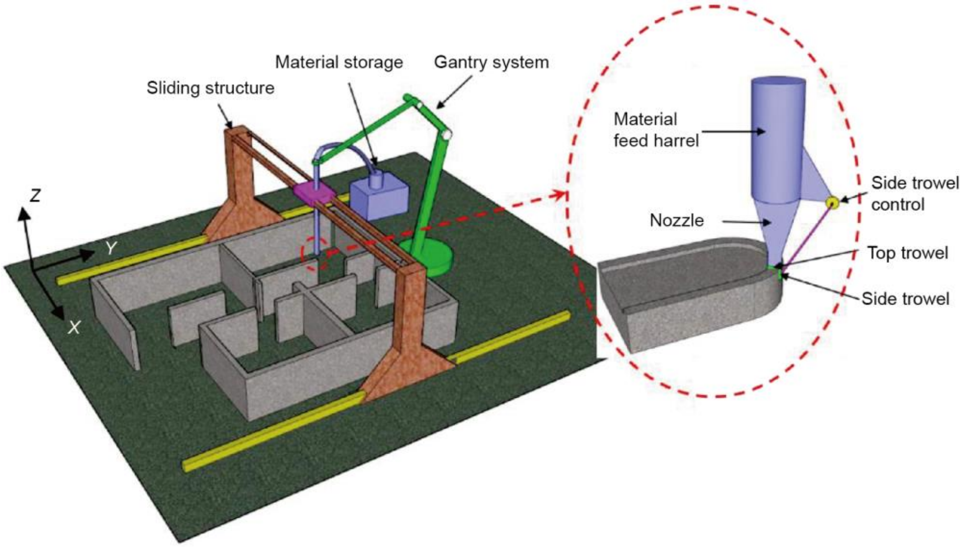


Figure 44 Construction of building using contour crafting printing **[103]**

A mobile CC platform driven by a translational cable-suspended robot was proposed by Bosscher et al. [137]. In comparison to other types of contour crafting systems, their CC system allows for major increases in portability, lower cost, and the construction of larger structures.

An overall performance enhancing systematic method for contour crafting systems was proposed by Zhang and Khoshnevis [138], this solution can provide an optimum printing operating plan for a single nozzle CC system and collision-free printing plans for multiple nozzle CC systems.

Several projects using contour crafting printing are seen in Figure 45.

Figure 45 Examples of full-scale builds from contour crafting printing **[103]**

(a) Concrete wall with a height of 60 cm, 2006 **[22]** ; (b) hollow walls with corrugated internal structure, 2013 **[61]**; (c) castle printed in-situ, 2014 **[139]**; (d) five-story apartment built by WinSun, 2015 **[140]**; (e) clay and straw wall, over 2 m and still growing, 2016 [31] **[103]**

6.2.2. Concrete printing

Another large-scale building method is concrete printing. The printing nozzle follows a pre-determined direction and extrudes concrete materials continuously. Since the printing head used for the extrusion of cement mortar is also mounted on an overhead crane, we can compare it with contour crafting. Both of them are based on cement mortar extrusion, yet concrete printing can handle resolution of deposition in a better way resulting in better controlling of complex structures.

Firstly, the piping system delivers the fresh concrete mix to the pump which delivers the printing material to the printing nozzle where it gets extruded out continuously to trace the cross section of the printed structure.

3D concrete printing works similarly to FDM in that it deposits the printing material through a nozzle to produce a structure without the use of formwork.

The method of concrete printing is shown in Figure 46 where we can see the printing head mounted in a tubular steel beam and can travel easily in the directions of x, y and z giving it the possibility of making highly customized building components [141] [142].

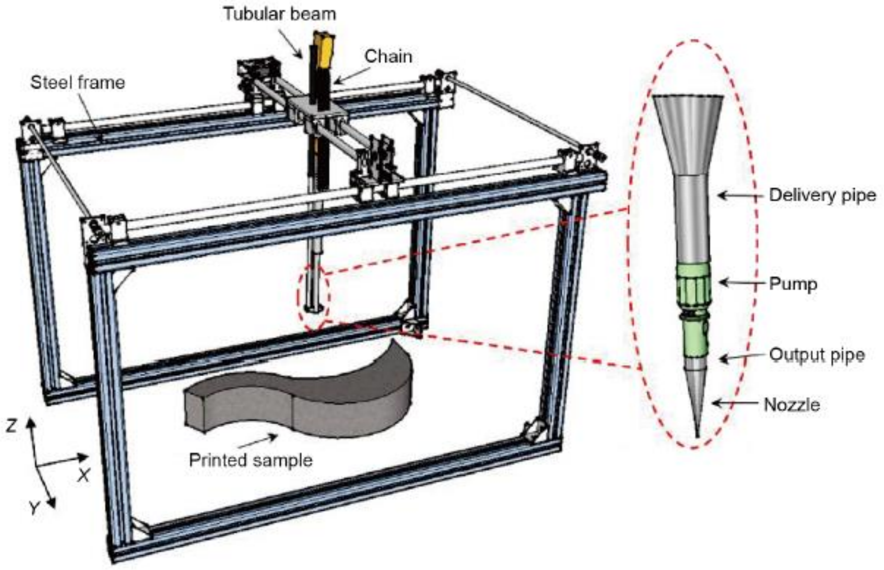


Figure 46 Schematic of concrete printing, magnified region is the concrete deposition system **[103]**

Engineer Alex Le Roux of Baylor University [143] invented and developed a concrete 3D printer that uses cement composite and can produce an entire 8×5×7 foot structure in 24 hours at a printing speed of 0.3 feet per second.

Massive concrete 3D printer was developed by a research team in Eindhoven University of Technology (TU/e) and it uses a four-axis gantry robot with its own mixing pump and a print bed of 9.0 m×4.5 m×3 m [144].

A new Concrete Printing system within a 5.4 m×4.4 m×5.4 m steel frame was developed by Lim et al. [142]at Loughborough University (UK). Figure 47(a) shows a printed structure named Wonder Bench that is made of 128 layers with an average printing speed of 20 minutes per layer.

Gosselin et al. [145] created a modern large-scale concrete printing technique in which ultra-high performance concrete is deposited using an extrusion print head attached to a six-axis robotic arm that can move the printing head freely.

Figure 47 3D components manufactured by concrete printing. (a) Wonder bench (2 m×0.9 m×0.8 m), 2015 **[61]**; (b) acoustic damping wall element, 2016 **[145]**; (c) curved-layered construction component, 2011 **[146]** **[103]**

6.2.3. D-shape

In this method, following a digital model, the printing head of the D-shape printer deposits a binding liquid using its spreading nozzles to selectively bind the sand together after the sand powder has been spread out to the thickness given by the software, which is a similar process to the Selective laser sintering SLS technique as D-shape printer selectively binds sand with magnesium-based binder to create structures.

The excess sand acts as a support for the structure during the printing process and it also can be reused for another production process after the previous one has ended [61].

The printer head is connected to the square base by a horizontal beam and has hundreds of spraying nozzles, the beam also allows it to travel easily around the X axis. Also, four stepper motors drive the square base upwards on the Z axis through vertical beams as explained in Figure 48.

Spraying nozzles selectively spray, on predefined parts of the sand layer, the liquid binding agent then before the next layer printing process happens, the horizontal beam acts as a powder material spreader [147].

As seen in Figure 48, D-shape produced in one single printing process a 1.6 m high freeform model and a whole house, indicating that D-shape is effective in printing structures on a large scale.

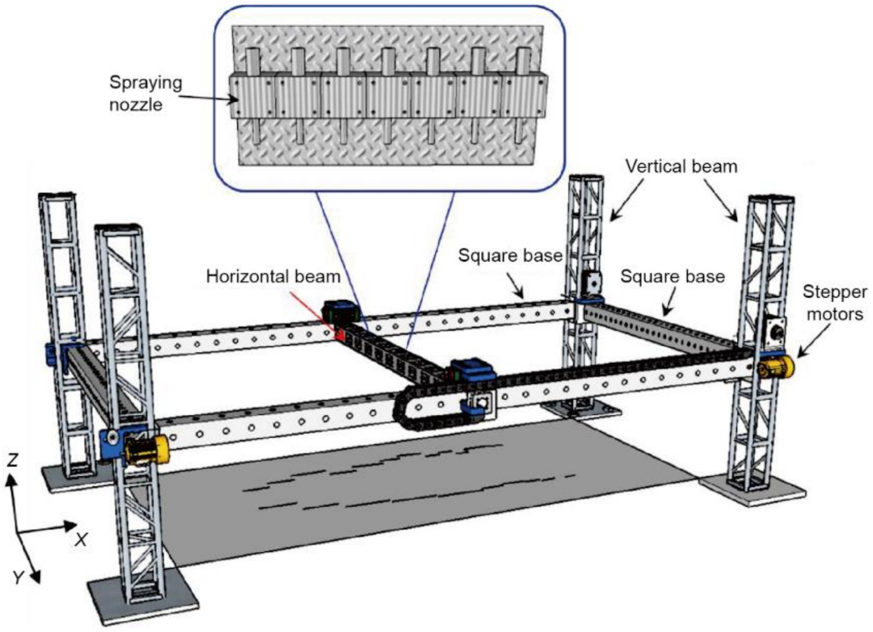


Figure 48 Schematic view of the D-shape printer **[103]**

The European Space Agency (ESA) funded a study project that was able to succeed in printing full scale parts for moon bases with simulated lunar dust through the use of D-shape. Despite the success of this printer in, its performance in the lunar environment is yet to be examined [147].

Also, D-shape is believed to enable military personnel to build facilities like hospitals, bunkers and bases much faster than they will using conventional methods [148].

Enrico Dini and Vittadello used a material consisting of sand, salt, and an inorganic binding agent to print out a variety of structural blocks used in building a futuristic-looking frame using the D-shape technique [149].

As seen in Figure 49, largescale structures manufactured via D-shape technology.

Figure 49 Largescale structures manufactured via D-shape technology. (a) 1.6 m high sculpture, 2008 **[61]**; (b) a complete house printed in one single process, 2010 **[147]**; (c) landscape house design based on a Mobius strip, 2017 **[150]**. **[103]**

6.2.4. Characteristics of large-scale 3D printing

Contour crafting, D-shape and concrete printing are the three main methods in printing large scale structures. Although all three of these production processes are similar in that they manufacture components in an automotive and layer-by-layer fashion; however, each process has its own unique characteristics that result in different advantages.

The contour crafting and concrete printing processes are currently fixed with a single large-diameter nozzle which means high speed in printing layers. While the contour crafting and concrete printing processes are fast, they have limitations in terms of printing resolution and layer thickness. D-shape has a better printing resolution because of the small nozzle diameters. As a result, obtaining appropriate printing speed and resolution is a challenge. Increasing printing accuracy would eventually lengthen printing time and require the printing of more layers.

In terms of printing size, contour crafting is the best method for achieving the biggest structures and it is the closest technique for printing buildings thanks to its multi-axis robotic arm while the other two methods, in terms of printed result dimensions, are severely limited by their deposition system and the mechanical frame.

In terms of deposition path, contour crafting method creates wall-like elements and structures and optimizes the time for that by outlining the entire layer with two passes of the printing head. Just one traverse is required to print the entire cross-section with D-shape, while concrete printing uses a single deposition nozzle as well, unlike D-shape, it must cycle through the entire construction area several times.

In terms of manufacturing over-hanging areas, printing an entire house with windows and roof at once is beyond the capabilities of contour crafting. On the other hand, The D-shape approach, which uses the unconsolidated powder surrounding the unfinished structures to support the whole object during the printing process, is a good solution to this issue, yet we have to consider one condition which is printer's dimensions should be greater than the printed structure in order for the process to be done in a single operation.

Table 2 Similarities and differences of largescale AM process in construction **[103]**

	Contour crafting	**D-shape**	**Concrete printing**
Process	Extrusion based	Selective binding	Extrusion based
Support	Vertical: No Horizontal: Lintel	Unused powder	A second material
Material	Cementitious material	Sand	High performance concrete
Printing resolution	Low (15mm)	High (0.15mm)	Low (9-20mm)
Layer thickness	13mm	4-6mm	5-25mm
Print head	1 nozzle	Hundreds of nozzles	1 nozzle
Nozzle diameter	15mm	0.15mm	9-20mm
Printing speed	Fast	Slow	Slow
Printing dimension	Mega-scale	Limited by frame (6m × 6m × 6m)	Limited by frame

Chapter 7
3D printing control strategies

The multi-parameter interdependency of the main parts of the 3DCP system (printer, material, and geometry) was investigated in a Dutch study [151]. Any of these parts has a set of parameters and variables and all these parameters together can be identified as the system parameters Figure 50, some of which could be entirely controlled and others are subject to effects that are too hard to control after a certain point. These parameter relations must be known and quantified in order to completely control the 3DCP process and predict both the printability and the characteristics of the printing geometry.

Many developments in the field of additive manufacturing of concrete AMoC seem to target low cost / rough quality applications, so this kind of knowledge and in-depth analysis can be debated as not necessary, but when it comes to applications with high quality requirements then the only way to ensure the quality needed is by understanding these dependencies.

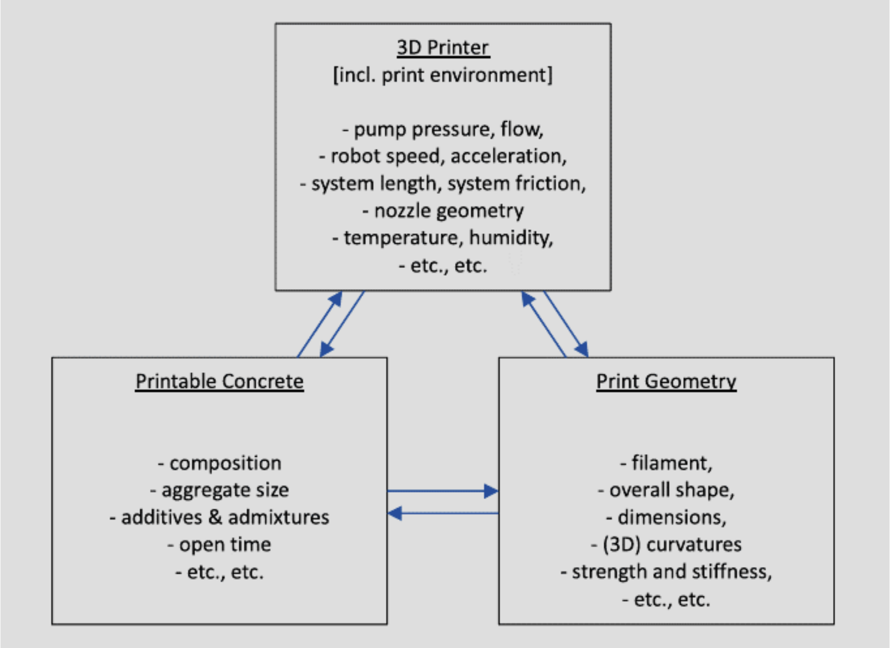


Figure 50 Interdependency of system parameters of the 3DCP system **[151]**

Process Modelling and Printing Strategies:

As shown in Figure 51, we should consider 4 levels of control of the system parameters in order to understand the issue of process control in 3D construction printing.

7.1. Levels of 3D printing system parameter control

7.1.1. Level 1: Predefined System Parameters:

Level 1 is the first and most basic level of control and ‘Predefined System Parameters’ is the situation in which a set of not fully known system parameters (concrete, 3d printer setting, geometry) is applied and some product will be printed, and results are hard to replicate, since the system parameters are only partly known. [151]

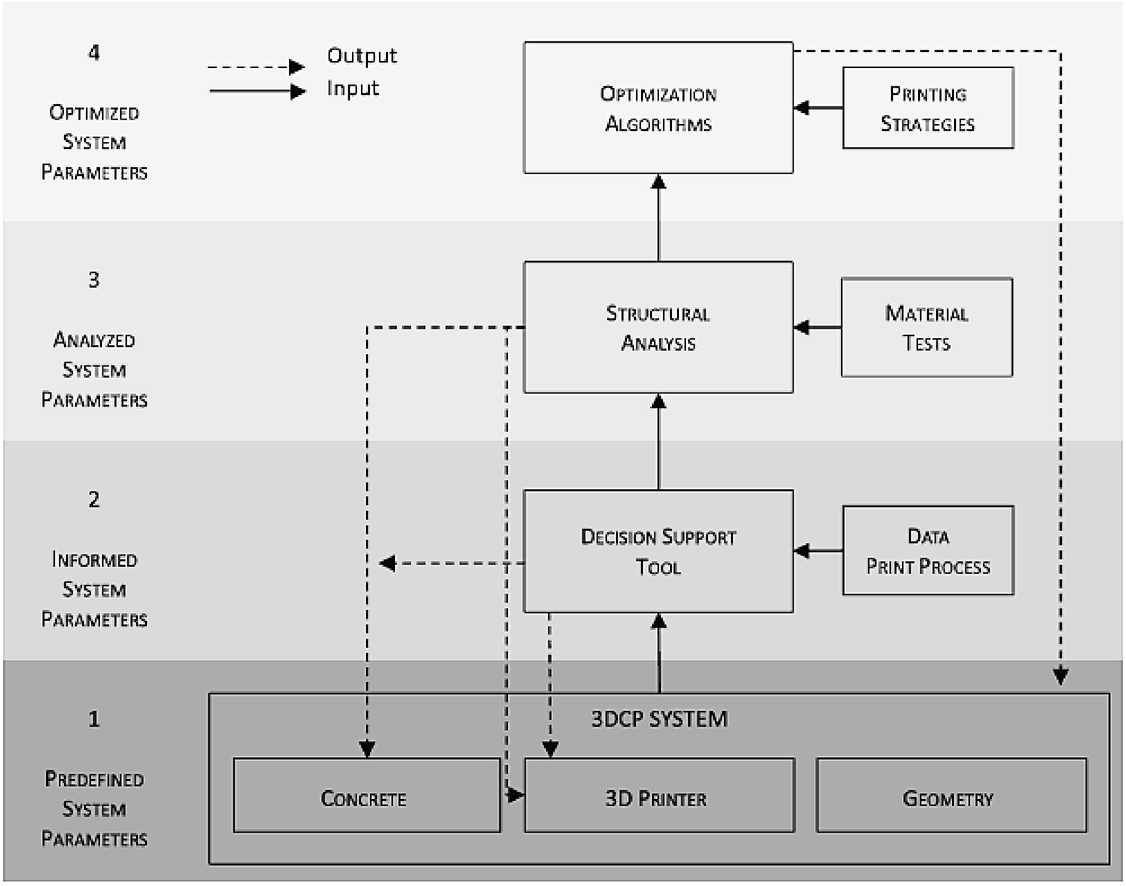


Figure 51 Levels of system parameter control **[151]**

This degree of control is a precondition for higher levels of control and can only be achieved by trial and error and. At this level however, a new trial and error process will be required for each new combination of system parameters which makes this level of control not adequate for both practical and scientific applications because it is basically not repeatable.

7.1.2. Level 2: Informed System Parameters

The second level of control requires to identify and quantify the most relevant system parameters like in the case of 3DCP system it’s necessary to identify and quantify: printer speed, pump pressure, system and ambient temperature and humidity, material composition (after mixing), printing path, nozzle height and geometry. [151]

This makes it possible for the user to replicate the procedure and the outcome under reasonable limits, which is a necessity to consider for the technology to be seriously thought of.

In a basic variant, based on basic parameter studies, fixed parameters are chosen.

For example, early on in the 3DCP study, the impact of pump pressure and print head speed on filament section measurements was determined in the manner explained in (Figure 52 and Figure 53). [151]

Getting a Decision Support Tool that helps you to determine how to change a certain system parameter to achieve a desired result in printing is critical to maintaining an informed level of control. Any of the Informed System Parameter forms (basic or more sophisticated) requires such a tool, yet this may be trivial for the basic variant.

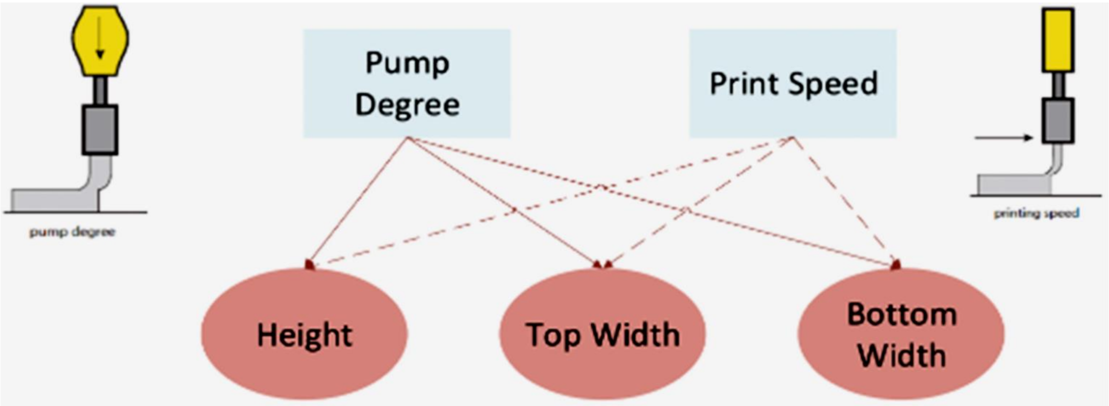


Figure 52 Simple scheme of printer parameter and geometry parameter relations **[151]**

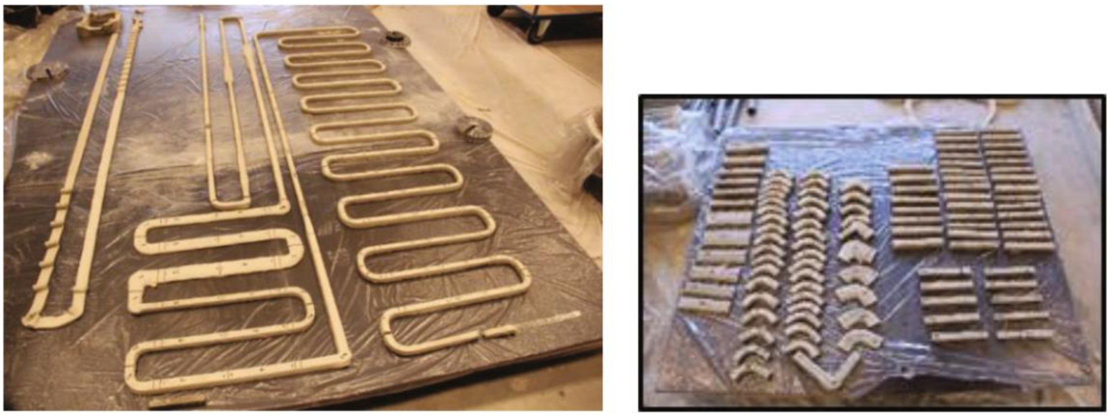


Figure 53 Collecting data on the cross-sectional geometry of filaments **[151]**

7.1.3. Level 3: Analysed System Parameters

Control levels 1 and 2 assume that the printing process and the behaviour and properties of the object being printed are not linked and do not affect each other. While in fact, the printing process has a significant impact on the printed item even when choosing a known geometry and vice versa, object properties during printing decide what can and cannot be printed.

the ability to analyse a print geometry in terms of printability and expected product properties are a requirement for level 3 control of system parameters. [151]

A preliminary FEA-based method has been developed to perform such studies at Eindhoven University of Technology [152]. It allows for the detection of both strength and stability failure modes, allowing for precise predictions of what geometries can be printed at what speeds (Figure 54).

Extensive experimental tests on fresh concrete with an age of between 0 and 90 minutes after leaving the print nozzle was used to model the material behaviour.

A uni-axial compression test and a shear-box test were custom developed since there were no appropriate codes or guidelines for obtaining these material properties (Figure **55**). Following that, in order to monitor object displacements during printing an optical measurement device had to be created and thus validate the FEA predictions, which preliminary findings indicate to be promisingly reliable (Figure 56). Also, to further enhance the precision, other parameters may be included in the method.

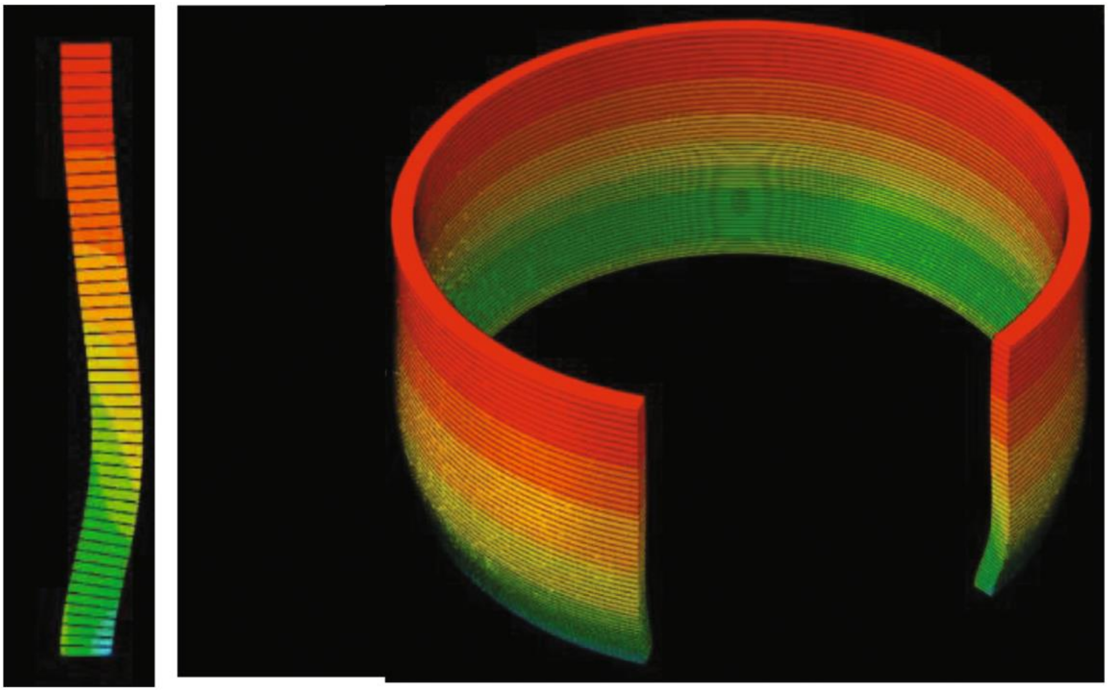


Figure 54 Time-dependent FEA of printing geometry **[151]**

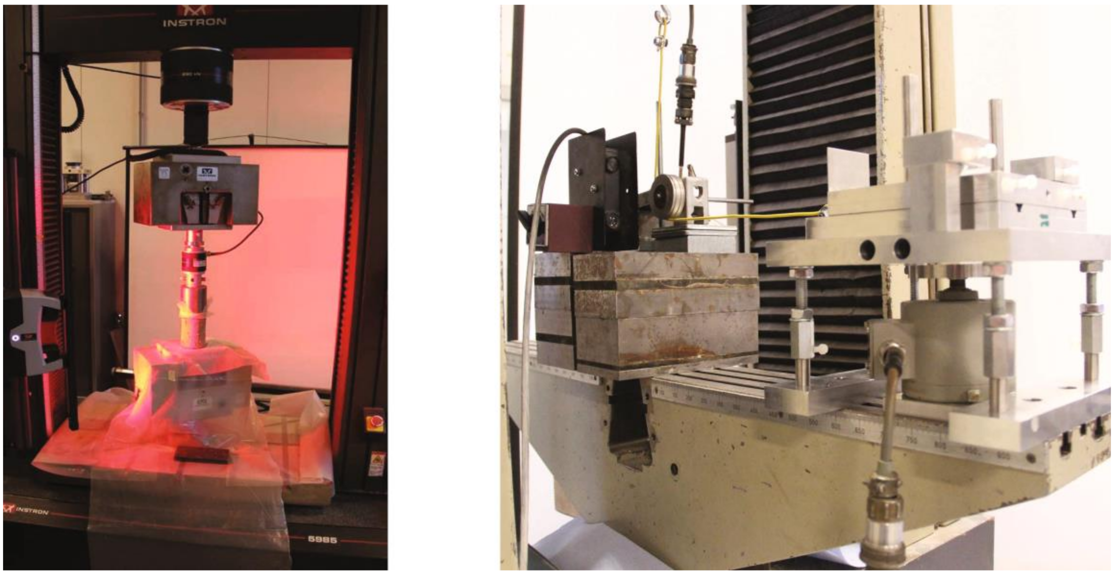


Figure 55 Custom developed uni-axial compression test and shear box test **[151]**

For the process modelling, end product quality dependency on print process parameters also needs to be established and not only the properties of the object during printing should be considered since the goal of process modelling is to predict both the printability and the end product quality. [151]

Material setting time, interface strength and interface interval time (time between subsequent layers are being deposited onto each other) should also be considered.

Experiments at the TU/e research have indicated that with the concrete mix used, tensile strength decreases dramatically with long interval times as in the case of several hours to days. However, this dependency disappears when the interval time is in the range of minutes. Taking in mind that other faster hardening material mixtures can be more sensitive to interface interval time.

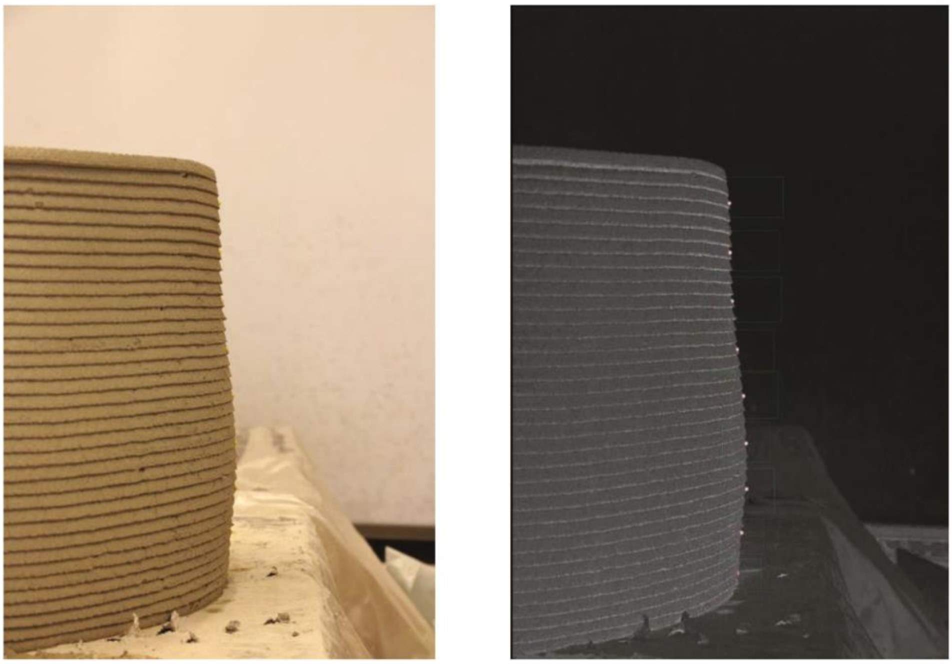


Figure 56 Tracking deformations of a printed object with optical measurements **[151]**

This means that conscious choices can be made to balance in-print and after-print structural requirements during the control level of Analysed System Parameters.

Another aspect to consider is that existing mentioned test methods for concrete are not specifically appropriate for 3DCP print geometries since they do not attempt to achieve the parameters that are most applicable to 3DCP geometries (Figure 57) and new test methods had to be developed.

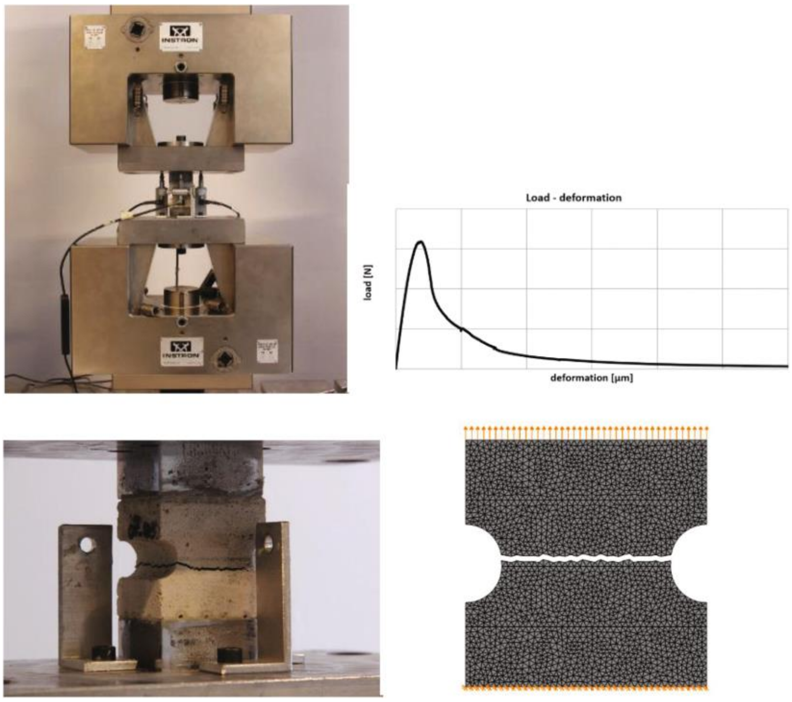


Figure 57 The development of structural tests on the bond properties in the interface **[151]**

By comparing conventional concrete construction to 3DCP we notice that in the conventional concrete construction, a structural analysis is generally only made once (for the end situation) and the object is made twice (as a negative – the formwork, and as a positive), while in the 3DCP, a structural analysis of the object must be made twice (during printing, and the final product) and the object is only manufactured once (as a positive).

7.1.4. Level 4: Optimized System Parameters

At this level, Instead of analysing a predefined printing protocol as in Level 3, optimization algorithms which may be generic or based on form-finding or topology optimization, are then used to establish system parameters, as It will be applicable to generate an optimal printing protocol directly from the end product's performance specifications like geometry and structural behaviour.

The input for the optimization algorithms can be acquired from printing strategies that describe the print process boundary conditions and structural models (to predict printability). [151]

The printing strategies can determine print path orientation, curvature limitations, maximum element sizes, filament resolution, cantilevering limitations etc.

When system parameter control is optimized, a print strategy is generated that, for example, adjusts the material formulation for the print, the print speed depending on which parameter is set by the designer to be variable, to the point that a printable configuration meets all set specifications.

Chapter 8

Potential applications, advantages and challenges of 3D printing in construction

8.1. Potential applications of 3D printing for cementitious materials

3D construction printing has demonstrated over many showcase projects the capabilities of this technology and its promising future and diversity of applications with the integration of automation control technologies.

8.1.1. Irregular shaped structures

3D printing is intended to be applied to complicated structures in order to manufacture irregular shaped forms that are difficult to be produced using the conventional methods like hollow walls with corrugated internal structure, acoustic damping wall elements, doubly curved cladding panels. Etc. [103]

8.1.2. Integration with building information modelling

Building information modelling BIM provides new ways to increase the building process' quality and efficacy.

Since BIM is powerful and effective in complex construction design and the ability to generate complex geometries is a big advantage in 3D printing, it is advised to use BIM to model the project, refine, and simplify the printing process in order to reduce printing time and reduce the repeatable delivery path in the printing process. [103]

When used in the field of construction and building, 3D printing combined with BIM will greatly aid design plan changes while also reduce the time and expense of the printing process since BIM can be used to control and optimize the entire process, from parametric design to printing of the building, with the goal of eliminating overlapping work and reducing wasted time. [103]

8.1.3. Adopting various materials for printing

At present, the large-scale 3D printing technology can be divided into two groups, the first method is based on wet cementitious paste extrusion, and the other one is by spreading dry powders and selectively gluing them with the selective spraying of liquid binding.

As we have mentioned before, the two aforementioned methods experiment and utilize a lot of materials in order to reach the wanted properties for the printed mix, such as recycled fine aggregate, blast furnace slag, polymer, limestone powder, tailing sand. Etc.

Also, in order to improve tensile strength and toughening effect of printed structures, glass fibre, basalt fiber, steel fiber and polypropylene fibers can also be mixed during the preparation process.

8.1.4. Application in planetary construction

Another potential technology area for 3D printing is planetary building. Habitat construction on the Moon and Mars has sparked renewed interest in recent years [153].

Another potential use area for 3D printing is planetary building as habitat construction on the Moon and Mars has sparked renewed interest in recent years since large-scale 3D printing provides the ability to create supportless structures out of on-site materials.

Figure 11 depicts a hypothetical NASA-sponsored 3D-print infrastructure project on Mars. Solar energy can be used to generate electricity for a large-scale 3D printer. The lunar dust can be used as a building material which can be sintered using microwaves to produce multiform structures. [154]

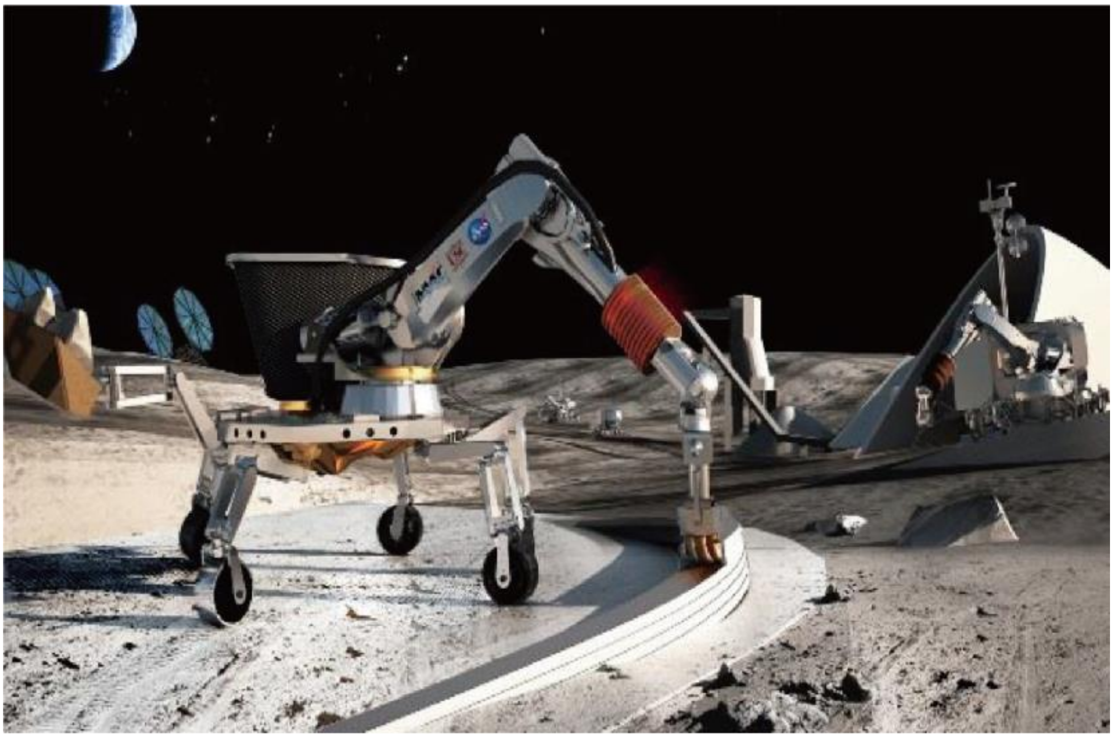


Figure 58 Imagine drawing of 3D-printed infrastructure project on Mars sponsored by NASA **[153]**

8.2. Advantages of 3D printing of cementitious material

Since 3DCP is still in the development stages, the integration of automation control technologies is plausible and even inevitable for 3D printing to continue growing in the engineering and construction industry. such as 3D scanning in the digital model acquisition process [155], swarm robots and mobile technology applied in the process of material transportation, 6-axis robotic arm used in structural components assembly process [156], wireless spatial location technology, computer numerical control technique used in the printing process [157]

This adoption will offer many opportunities and give 3DCP advantages over current construction techniques.

8.2.1. Social impact

3D printers are electric-powered systems that produce basically no emissions which means a significant environmental and social impact and can result in near-zero material waste due to its precise construction technique. Also, it significantly reduces noise pollution produced during the construction phase as current on-site building operations would eventually emit a variety of harmful emissions, as well as a considerable quantity of unused formwork and solid materials [158].

Results of Life Cycle Analyses (LCA) show that total demand for energy of 3D printed products can be decreased by 41 percent to 64 percent, thus minimizing environmental impacts [159].

The four stages that an industry goes through, according to the life cycle theory, are: start-up stage, growth stage, mature stage and degenerating stage.

3D printing is currently in the start-up phase in the building industry. For 3DCP, progressive innovations and growth are needed to exploit its full potential and thus gaining the maximum environmental benefits and social benefits.

8.2.2. Design flexibility

The layer based method of 3DCP allows for a high level of versatility in architectural design and allows for the construction of civil engineering structures with a variety of architectural forms that are difficult or impossible to create using existing manual construction methods [160].

The most important advantage offered by 3D printing for large-scale construction is design freedom and freeform construction rather than speed or material. This kind of flexibility cannot be matched by other methods and it compensates for the limitations of 3D printing as It offers architects and engineers almost limitless options for dealing with geometrically complex structure [161].

8.2.3. Cost benefit

3D printing provides automation of construction. The cost of existing strategies would also be reduced by the following three aspects:

In terms of labour costs, 3D printing's highly automated process will greatly minimize the amount of manpower used in the building process.

3D printing will considerably accelerate the building process in terms of time costs. The construction method takes reportedly one quarter of the necessary time to construct a traditionally comparable structure [161], [162].

In terms of difficulties arising from mistakes, the automated system minimizes unnecessary work and the material waste by reducing the effects of human error in the construction process.

In terms of material costs, the amount of raw materials used to fabricate products can be accurately measured before the printing process starts, and material can be precisely deposited to the correct spot during the printing process, resulting in lower material usage and less waste [163], [164].

An experiment for the building of a 40 MPa concrete wall between conventional method and 3D printing method was done by Camille et al. [103] in order to do a cost comparison (see Table 3).

Table 3 Cost estimates for construction a wall from 40 MPa concrete using traditional method and 3D printing **[103]**

	Traditional method			**3D printing**		
	Cost	Amount	Price	Cost	Amount	Price
Supply of concrete	200$/m³	150 m³	30000$	250$/m³	150 m³	37500$
pumping	20$/m³	150 m³	3000$	20$/m³	150 m³	3000$
Labour	20$/m³	150 m³	3000$	-	-	-
Formwork	100$/m³	1500 m³	150000$	-	-	-
Total			186000$			40500$

Based on the data shown, the total cost of a concrete wall built using 3D printing is basically a quarter of the cost of a conventional building process.

3D printing concrete parts will save almost all of the labour and formwork costs as it takes 35% – 60% of the total cost of concrete structures according to rough statistics [165].

The breakeven relationship between traditional and additive manufacturing processes is depicted in Figure 59.

In traditional manufacturing methods, the expense of each additional unit of production declines with the overall growing number of produced objects, while the cost per unit rises as the complexity of the object rises.

In contrast, the cost of 3D printing remains relatively constant for each unit produced with the overall amount and complexity having little effect on the cost.

As a first step in the adoption of this technology, we can notice current 3D printing presence in low to medium sized manufacturing and relatively complex structures. Also, in the future manufacturing costs for 3D printing will gradually decrease as the adoption rate and throughput of 3D printing will continue to increase [166] [167].

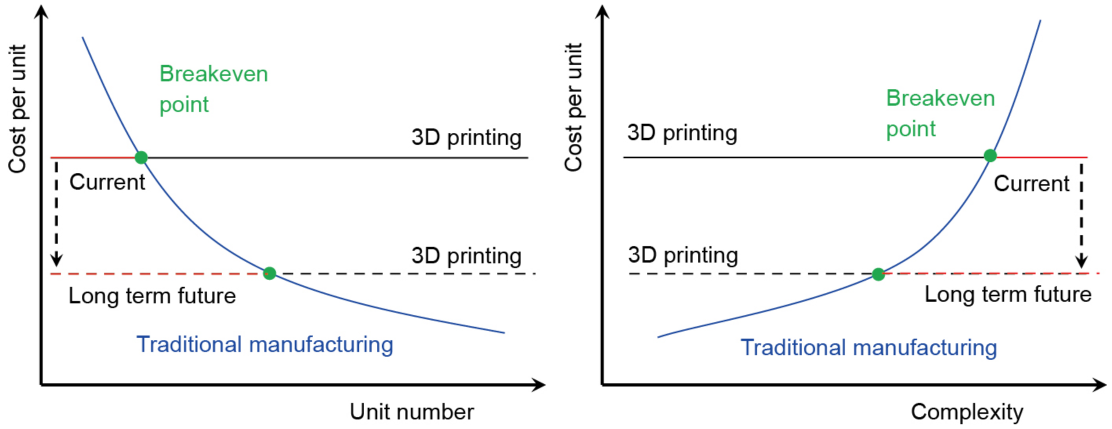


Figure 59 Breakeven analysis comparing conventional and additive manufacturing process **[103]**

8.3. Challenges of 3D printing for cementitious material

While large-scale 3D printing for cementitious materials has some obvious advantages and potentials in the building and construction industry, there are still some difficulties and challenges that prevent its use from spreading.

8.3.1. Cementitious material compatible with 3D printer

The most important limitation of 3D printing in construction is compatible cementitious materials as It's a crucial task to balance wet-properties of cementitious material (such as being easy-flowing, easy-pumping, easy-deposition, dimension stability and low-shrinkage) and optimize it to work with the printing system. [103]

The printing materials setting time, for example, should be sufficiently optimized to enable the transportation in the delivery system and decrease blockages in pipes, as well as the setting time should be short enough to quickly harden the printing paste so that the following layers can be supported without collapsing.

Cement-based mixtures have been improved and have proven effective as a printing material. However, because of the types of raw materials and the adoption of printing admixture, the 3D printed structures were more expensive than those created by commonly used materials.

As a result, low-cost, viable, and easily obtained construction materials, such as recycled building materials, tailing sand, and waste rubber powder, must be developed.

8.3.2. Implementing reinforcement

Reinforcement is another obstacle for 3D printing to overcome when it comes to replacing existing building methods for load-bearing structures as extruded cementitious paste cannot produce a conventional reinforced concrete structure and the printed structures are fragile and weak to tension.

This topic was addressed by existing large-scale AM. Extra robotic arms are used in contour crafting to embed steel supports in the construction process. Furthermore, concrete printing leaves some voids in the printed components to allow for the post-insertion of steel bars to increase tensile capacity. [61] [168]

8.3.3. Design of mega-scale 3D printer

In the world of engineering and construction industry, 3D printing methods are currently only used to create structural components and low-rise buildings and may not be suitable for high-rise residential or other large-scale construction projects [169] [170] as the size of building or project that a 3D printer can print is severely limited by its size and current printers.

Mega-scale 3D printers are expected to be transportable and able to be set up on site to meet the demands of construction site operations. [103]

3D printing real architecture and realizing the construction of high-rise buildings relies on addressing a number of challenges, including the optimisation of the material storage, distribution and deposition system and ensuring stable climbing of 3D printer. [103]

8.3.4. Development of evaluation standards

Conventional concrete material and printed structures should not have the same evaluation standards and testing methods, since regular cement composite are different from cementitious materials used for 3D printing in respect to raw materials, mix method, cast process, etc. So, in order to test and evaluate the mechanical performance, rheological performance, and long-term service behaviour of printing materials, new standards and regulations must be revised. [171] [172]

These new specifications and regulations are intended to ensure that printed materials and systems have sufficient bearing capability to withstand a variety of complex loads, such as gravity, snow, wind, and seismic activity, as well as to meet the reliability criteria for carbonization, corrosion, freezing. etc.

8.3.5. Coordination of printing precision and efficiency

The precision of printing is directly related to the accuracy of printed structures. Higher precision printing can ensure greater accuracy of printed structures but at the expense of decreased construction efficiency and increased final cost. [103]

Printing speed will likely come at the expense of printing precision. As a result, model design must take into account both machinery control precision and production speed in order to maximize the potential of automatic construction. [103]

Chapter 9
Conclusions

As a conclusion, through the historical overview, the rapid development of the 3DCP in the past ten years has been observed due to the spread of digitalization and social media coverage.

Therefore, attention should be paid to the advanced technologies and digitalization approaches, and research results in these fields should be widely spread and covered by all media platforms to encourage investors and researchers to adopt the advanced technologies, especially the 3DCP.

Despite all the advantages of 3DCP mentioned in this work, it became clear that the engineering and construction sector was unable to fully localize it since there are many difficulties to overcome like finding a compatible material, scale limitation of the printer, implementing reinforcement, development of evaluation standards or coordination of printing precision and efficiency.

Therefore, it was concluded that efforts and research should be intensified to develop all components of the 3DCP, from materials to printers and methods of printing, with a focus on integrating advanced technologies with the 3DCP to complete each other.

Also funding for these researches should also be increased to accelerate the achievement of the maximum effectiveness of this promising technology.

This thesis has explored the development of 3D Printing particularly in the construction sector throughout the years and collected the most important achievements in this method in order to know where the current approaches are in relation to the evolution of this technology and to evaluate its readiness for the implementation in the engineering and construction industry, to the author best knowledge, there is no a comprehensive state-of-art that collects this information into one work in such a way.

To address the stated objective, first, a historical overview of 3DCP was covered, from the beginning of the twentieth century when the idea of printing three dimensional buildings was just a story in a science fiction literature until the recent days, two main milestones were found:

- The first real attempt to automate 3D concrete printing process developed in 1995, which used sliced geometry created with CAD software.
- The true digitalization of the construction process becoming feasible (e.g. BIM) during the first half of the twenty tens.

From the historical overview, an especially important aspect for accelerating the development of this technology was noticed, which is the rapid spreading of early results via social media, making the number of parties associated with 3D construction printing to increase quickly and starting a technological race to design a printer that can produce inhabitable buildings.

By reviewing the development of this technology in finding materials that meet the requirements of 3DCP, the following considerations were observed:

- Traditional building materials are considered primitive and lack many properties to become suitable for the use of 3D printing.
- The most important design methodologies of cementitious materials are extrudability control, flowability control, buildability control, setting time control, mechanical property control, shrinkage control and optimization for mixture proportion.

In case wet of cementitious paste extrusion methods, the key aspects for an effective printing material are fresh concrete properties like buildability, flowability and extrudability with a mix design which can meet the need for prolonged working-ability before setting for extrusion while maintaining high early strength in subsequent layers without structural collapsing and failure.

Also, rheological properties of the concrete mix, particularly the thixotropic behaviour affects the pumping and printing of the mixtures.

Another key aspect for effective 3D printing is structural features such as strength, adhesion between the layers, deformation, and durability of 3D printed structures.

Also, three promising methods for 3D printing in the construction sector were found, each method has specific characteristics and a specific use and all of them are under consistent development:

- Contour crafting: is best for achieving the biggest structures and it is the closest method for printing buildings. It provides a high level of surface quality, fast construction time and a large selection of optional materials, yet it cannot manufacture over-hanging areas in one printing process.
- Concrete printing: Another large-scale building method, can handle resolution of deposition in a better way than Contour crafting but it is slower and size limited by its frame.
- D-shape: has the highest printing resolution and since it uses sand with a liquid binder it has a lot of potential use in harsh and deserted areas so it attracted space agencies and military institutions. However, it requires more time and its printed product size is limited by its frame.

In General, to exploit 3D construction printing to its full potential, 4 levels of control of system parameters should be taken into consideration: Level 1: Predefined System Parameters, level 2: Informed System Parameters, level 3: Analysed System Parameters and level 4: Optimized System Parameters

These four levels of system parameters can define the predictability and repeatability of any 3D printed product which reduces drastically the material usage/waste and produces the ideal structure for the intended use.

Also, potential applications of 3d printing for cementitious materials had been discussed like irregular shaped structures, integration with Building Information Modelling (BIM), adopting various materials of printing and application in planetary construction.

Although 3DCP is not ready yet to be fully implemented since it has a lot of difficulties to overcome like finding a compatible material, scale limitation of the printer, implementing reinforcement, development of evaluation standards or coordination of printing precision and efficiency, yet the social and environmental impact such as zero emissions, reduced noise pollution, near zero material waste and economic benefits with the design freedom, gives this method a huge value for the industry to invest in.

In general, the future of additive manufacturing in the construction sector is huge, where every project is different with complex structures and different functionalities and with the arrival of this technology today, we must exploit it in the largest possible way and employ it in all industries so that we can overcome the difficulties and challenges facing the current society and secure a suitable life environment for future generations.

Finally, a state of the art that includes the main information about 3DCP has been done, collecting both new and old research in one work, focusing on the most important milestones that have been achieved in this technology, and highlighting the current position of this technology in the engineering and construction sector.

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