KARELIA UNIVERSITY OF APPLIED SCIENCES
Degree Program in Civil Engineering

Amirahmad Teymouri

POTENTIALITIES AND RESTRICTIONS OF CONSTRUCTION 3D PRINTING

Bachelor's Thesis
October 2017

Karelia
UNIVERSITY OF APPLIED SCIENCES

THESIS
October 2017
Degree Program in Civil Engineering

Tikkarinne 9
80220 JOENSUU
FINLAND
(013) 260 600

Author(s)
Amirahmad Teymouri

Title
Potentialities and Restrictions of Construction 3D printing

Commissioned by
Karelia University of Applied Sciences

Abstract

3D printing techniques (also known as additive fabrication) have been increasingly used as an alternative in product manufacturing. These fabrication techniques are now being scaled up and adapted for full-scale fabrication within the construction industry.
Potential advantages of these technologies include rapid construction, lower labor costs, increased accuracy, greater integration of function and less waste produced.

There has been significant effort invested in the development of construction 3D printing techniques. Researches have demonstrated that construction 3D printing may be well suited for construction of extraterrestrial structures on the Moon, Mars or other planets, where environmental conditions are less conducive to human-labor intensive building practices.

The original contribution of this research is survey of practices, literature reviews and emerging trends within the 3D construction printing, potentials, and restrictions. These practices and surveys have been tested through the design of unique architectural projects focused on fabrication using construction 3D printing.

Language	Page
English	46

Keywords

construction 3d printing, concrete printing, large-scale 3d printing, additive manufacturing

CONTENTS

1 INDEX OF TERMS

‘Additive fabrication’[1]

3D printing techniques (known as rapid and layered method) will be used for professional fabrication and also large scale printing in construction applications (construction 3D printing).

‘Rapid prototyping’

New automation approach is layered fabrication, generally known as rapid prototyping.

‘CAD’

Computer aided designing

‘CAM’

Computer aided manufacturing

‘Production territory’

A particular type of area to produce a product.

‘Offsite construction’

Refers to structures built at a different location than the location of use.

‘Modular buildings’

Or modular homes are sectional prefabricated buildings, or houses, that consist of multiple sections called modules.

---

[1] There are many more terms (additive manufacturing, rapid prototyping) that have been coined for this field of fabrication techniques, which will not be discussed here. These terms are the most commonly used to describe prototyping, tool building (tooling) and fabrication processes.

‘M&E work’
Monitoring and evaluation (M&E) is a process that helps improve performance and achieve results.

‘C&D’
Construction – demolition

2 INTRODUCTION

In the future, we do not want to design a building as we have learned so far. Instead, we will need solutions for implementing any imaginable design. We can expand our knowledge of additive manufacturing through encouraging researchers, teachers, and decision makers in universities and other organizations. We need to have more studies and explorations to solve today’s largest challenges of additive manufacturing, and eventually transferring invented technologies to conventional construction sites and disrupt the civil engineering industry. Indeed, there are still initial steps in the additive manufacturing and fabrications.

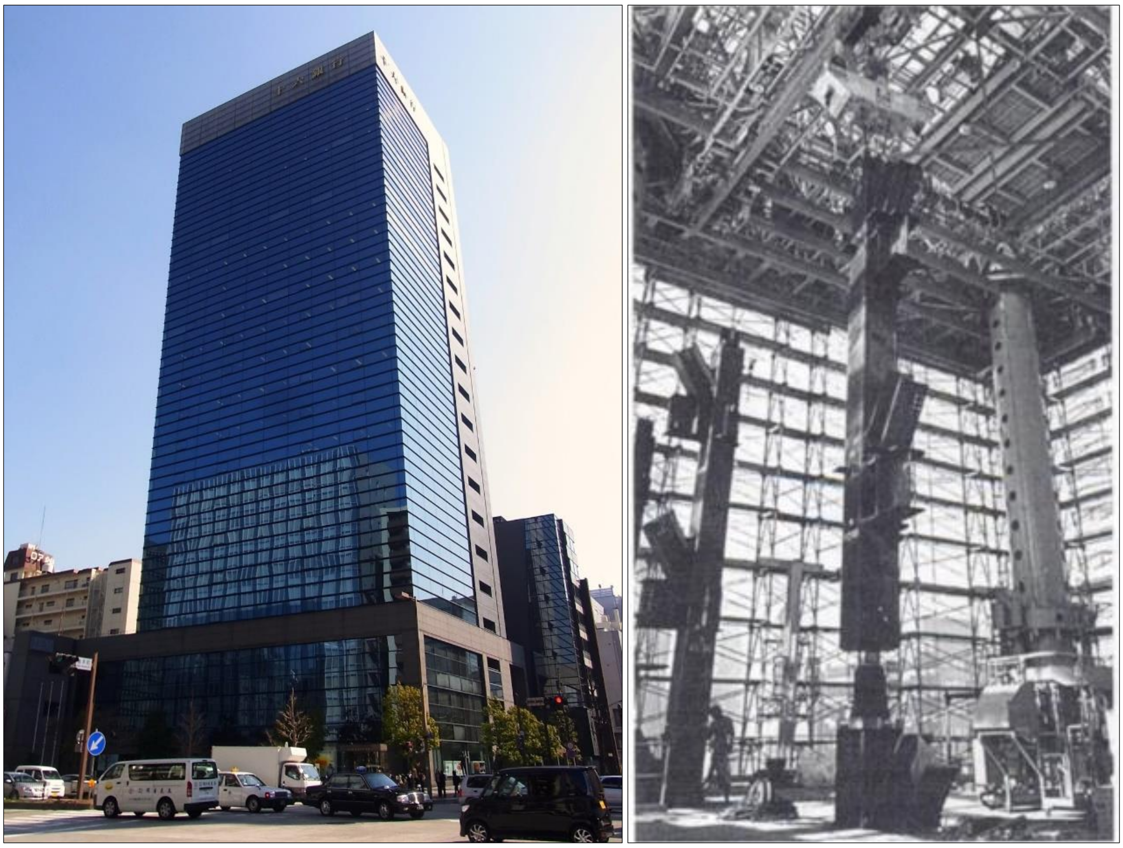
Today quite a lot of the manufacturing and production around us are automated, but the only things still made by hand are buildings. Since the early years of the twentieth century automation has grown and succeeded in almost all production territories other than construction of civil engineering structures. In civil engineering, especially in mining, tunneling, earthworks and road construction, mechanization has been successful. In the production of construction materials such as cement, steel, aluminum, glass and wood, the degree of automation is very high – almost up to 100%. Automation and robotics in the prefabrication of constructions and building components is high in precast concrete element production.

Building is not only limited to the construction industry. As a matter of fact, construction industry is acting as the focal point to join forces across different industries to make it possible to have housing solutions that are sophisticated in design, smart, economical and environmentally friendly.

In this study, potentials and restrictions of additive manufacturing and automation in construction industries are investigated. Also, today’s technique methods are briefly studies as well as the latest updates and innovations about large scale 3D printing in current companies, institutes, nonprofit groups and among academic researchers who are focused on developing those techniques. There are many issues that automation can solve in construction industry: labor inefficiency, accident rate at construction sites, construction quality, inefficiency in controlling construction sites and lack of skilled workforce.

3 HISTORY

Large scale automated manufacturing systems are not entirely new in the field of construction. In fact, automated manufacturing was invented by Shimizu Corporation, one of the Japanese construction companies. (Cousineau & Nobuyasu 1998, 49–54.)



Picture 1. The Nagoya Juroku Bank building. Completed 1993. The Shimizu Manufacturing System by Advanced Robotics Technology (SMART) system of the Shimizu Corporation controls all phases of building construction from underground work and superstructure work to finishing and M&E work. Building type: office, number of stories: 20, structure: steel frame, Height: 88m, total floor area: 20000 m2. Image (a) by Umako (Own work) via Wikimedia Commons. Image (b) Cousineau, L & Nobuyasu, M. 1998. SMART system's steel erection. Construction robots, the search for new building technology in Japan. Chicago Institute & Kokushikan University. United State of America. The American Society of Civil Engineering. 1998.

The SMART system is the first automated construction system to be applied to a full-scale building project. Juorku Bank building (Picture 1) was completed by using a combination of automated and conventional methods. The portion of work that was automated included erection and welding of the steel frame structure, placing of concrete floor plans, and installation of exterior wall panels. The SMART system uses five innovative technologies: an automated lift up system, an automated transport system, a steel assembly system, an automated welding system and computerized information management system. (Cousineau & Nobuyasu 1998, 49–54.)

Several major construction companies in Japan have followed the development of systems based on similar ideas and up until now, there are many proposals.
The Shimizu Manufacturing System by Advanced Robotics Technology (SMART) system of the Shimizu Corporation controls all phases of building construction from underground work and superstructure work to finishing and M&E (monitoring & evaluation) work. It also controls various construction management tasks for the automated construction of high rise buildings. (Cousineau & Nobuyasu 1998, 49-54.)

3.1 Construction revolution

There has been, for many years, a lot of activity in the development of robots and automation for construction work. With this basis of automation technology, for instance aim is to achieve maximum integration of the various technologies which lead modernization of construction. For example, technologies for industrialization and systematization of the various components of building and computerization of site management. (Maeda 1994, 457-464.)

Construction 3D printing techniques have been in development since the mid 1990's with two separate techniques published in that decade. The first was a novel technique based on the deposition of sand and cement with selective curing of this material using steam; however, the technique was not developed further afterwards. The second was a gantry controlled concrete deposition technique called Contour Crafting ™ (Picture 2). (Gardiner 2011, 80.)

Picture 2. (a) Early version of the extrusion nozzle and machine. Images courtesy of Dr. Khoshnevis, University of South California. (b) The ContourCraft deposition head. Image: contourcraft.org

In total, eight separate construction 3D printing techniques have been invented, but only three of them have been developed: Concrete Printing, Contour Crafting TM and D-Shape TM. These three techniques focus on construction purposes and are in use. Those three techniques are described and discussed in detail below. (Gardiner 2011, 82.)

3.2 Technical methods

3.2.1 Contour crafting ™ (Extrusion based)

The Contour Crafting technique has been developed under the principal direction of Dr. Behrokh Khoshnevis at the University Of Southern California Viterbi School Of Engineering in the USA. The technique was unveiled in 1996 and is the oldest technique under development. To date the team have demonstrated a number of straight and curved wall sections and a scaled down adobe type structures. The development team, headed by

Khoshnevis have published proposals including single dwellings, multistory buildings and shelters for construction on the Moon or Mars. (Gardiner 2011, 82.)

3.2.2 Concrete Printing

The ‘Concrete Printing’ technique has been under development at the Additive Manufacturing Research Group at Loughborough University in the United Kingdom since 2004 within the Wolfen School of Mechanical and Manufacturing Engineering. The project was first conceived under the name ‘Freeform Construction’ machine with the assembly of the first machine commencing in 2006.

Fabrication with the concrete printing machine works on the basis of selective deposition of a paste material through an extrusion nozzle, in a similar way to that of Contour Crafting discussed above. The major difference between Contour Crafting ^{TM} and Concrete Printing is the nozzle design. The Concrete Printing nozzle (Picture 3) is designed to have the capacity to vary its resolution to allow the deposition of both bulk materials and fine details within the same process. (Gardiner 2011, 85-86.)

Picture 3. 3D Concrete printing developing large scale additive processes for the manufacture of building components. Developed at the additive manufacturing research group at Loughborough University. Image source: Loughborough University, 3D Concrete Printing: an innovative construction process buildfreeform.com/index.php

The work has already delivered 3D concrete printing, and additive manufacturing process capable of producing full-scale construction and architectural components. Current work is focused on novel reinforcement techniques, material science and the development of robotics for material placement.

3.2.3 D-Shape ™ (Powder based)

An Italian inventor, Enrico Dini, chairman of the company Monolite UK Ltd, has developed a huge 3D printer called D-Shape that can print entire buildings out of sand and an inorganic binder. His first construction 3D printing technique obtained patent in 2006. The printer works by spraying a thin layer of sand followed by a layer of magnesium-based binder from hundreds of nozzles on its underside. The glue turns the sand to solid stone, which is built up layer by layer from the bottom up to form a sculpture, or a sandstone building. (Picture 4) The problem with the process Dini stated was epoxy resin sticks to anything including the machine that is applying it.

Picture 4. (a) The second-generation of D-Shape machine was the world's first large scale 3D printing technology. Developed by civil engineer Enrico Dini. Image by D Shape. (b) Villa Roccia and Gaudi Tribute one of the D-Shape ™ project. The building blocks were 3D Printed and temporary assembled. The local authority did not give the permission to build and the project was terminated. Image by Monolite UK Ltd.

The Radiolarians sculpture (picture 5) is a significant scaling up of the demonstrated capabilities of construction 3D printing techniques to date. The sculpture is now planned to reach a height of 8.5 meters for a roundabout in Italy. (Gardiner 2011, 93.)

Picture 5. Full scale radiolarian assembly at D-Shape factory, Italy. Image source: J. B. Gardiner PhD thesis "Exploring the Emerging Design Territory of Construction 3D Printing, 2011

The principal concept of house 3D printing of D-Shape has shifted to the Archi-nature invention finally today. Enrico Dini has created a new concept of architecture, this new concept is ecological and it is called Archi-nature. Dini believes that if we are not able to create fantastic machines we are at least able to make very rough objects with the existing machines, and these are totally environmentally friendly. (Figure 1) (Dini 2013)

Figure 1. Archi-nature design is nature friendly, Enrico Dini says. Image source: Youtube.com, Large Scale 3D Printing: Enrico Dini at TEDxBocconiU

3.3 Latest innovations

Today’s new generation innovation in construction 3D printing and most relevant large-scale printers and construction 3D printers are using the discussed techniques above to manufacture a house or a building. For instance:

- Cazza construction technologies
- CyBe team
- DUS architecture
- Free Fab Wax ™
- BetAbram ™
- MX3D
- Passive Dom
- Apis Cor
- Winsun ™

3.3.1 Cazza construction technologies

Cazza provides the world’s next-generation large-scale 3D printing construction technologies and services to make construction faster, more cost-effective, and environmentally friendly. Cazza wants to automate as much of the construction process as possible, from laying down foundation to building walls. The company has developed its own proprietary construction material: a concrete-like substance that it says is up to 80 percent recycled material. Cazza is also working on setting up its own in-house facilities to manufacture its construction material and hardware. In addition, the company is developing new machines that can automatically set up plumbing and electricity, as well as new construction materials. (Xiao 2016)

Another one of Cazza’s products, a portable, crane-like 3D printer, can extrude this material into walls, layer by layer. Through the company’s software, users can design their own 3D models, or draw lines where they want material printed and at what height. According to Cazza, the company’s 3D printing machine can build a 100 square meter house within 24 hours. (Xiao 2016)

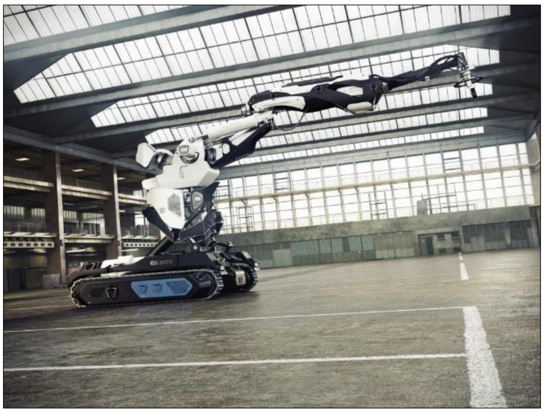


Figure 2. 3D printing construction robot developed by Cazza, called Cazza X1. Image by Cazza construction technologies.

Instead of printing pieces of the house in warehouses and trucking them to the construction site, Cazza says it can build directly on site. Moreover, by automating the construction process and 3D printing buildings, the company claims it can drastically reduce the amount of waste, pollution, and cost involved in the traditional construction process. (Dutt D'Cunha 2017)

3.3.2 CyBe team

CyBe Construction has developed the first mobile 3D concrete printer (Picture 6) which is able to move on caterpillar tracks: the CyBe RC 3D printer. This makes it easy to 3D print on-site. The mobile printed also has a high printing speed and an extended printing range. With this mobile 3D concrete printer it is possible to print among others high walls, on-site sewer pits and formworks against lower costs and in a shorter amount of time. 3D concrete printing is capable of increasing the quality of the product and is more eco-friendly thanks to reduction in CO2-emission and waste. (Saunders 2017)

Picture 6. Mobile concert printer developed by CyBe. The R & Drone laboratory construction field in Dubai which is CyBe announced on 02.06.2017 is printed and featured in an article: 3dprint.com, CyBe Construction Announces That 3D Printing is Complete for Dubai's R & Drone Laboratory 2017.

By developing, applying and offering mobile and modular 3D concrete printing techniques CyBe Construction offers new solutions and redefines the construction industry. This way of construction is much cheaper and faster than traditional methods while retaining the same high quality of the concrete. CyBe wants to facilitate the construction industry with state-of-the-art technology so they can create the construction components or even buildings faster, cheaper and more sustainably. (Saunders 2017)

3.3.3 DUS architecture

Dutch studio DUS Architects has 3D printed an eight-square-meter cabin and bathtub in Amsterdam, and is now inviting guests to stay overnight. DUS Architects used sustainable bio-plastic to create the 3D Print Urban Cabin, which is intended to demonstrate how additive manufacturing can offer solutions for temporary housing or disaster relief. When the cabin is no longer needed, it can be destroyed and almost all the materials can be reused. "The building is a research into compact and sustainable dwelling solutions in urban environments. Entirely 3D printed with black colored bio-based material, it showcases different types of facade ornament, form-optimization techniques, and smart solutions for insulation and material consumption," said the team. (Frearson 2016)

Picture 7. (a) 3D printing canal house nozzle called kamermaker is printing one of cabin piece which will be assembled like a puzzle. Image by demeeuw web magazine. (b) Printed 8 m2 urban cabin by DUS architects team through kamermaker in Amsterdam. Image by: Sophia van den Hoek (c) DUS Architects has mixed 3D-printed bioplastic with a tensile fabric structure to build a sculptural facade for the building where European Union meetings will take place soon. Image by DeZeen.com, Dutch EU building features a facade combining tensile fabric and 3D-printed bioplastic, 2016.

3D Print Urban Cabin is not the first completed example of the studio's 3D printing expertise – earlier 2016 it created a sculptural facade for a European Union meeting building, which was the first public reveal of its so-called "XXL 3D prints (Picture 7). This technique uses fused deposition modelling, the same form of additive manufacturing used by most household 3D printers. The cabin is available for short term. (Frearson 2016)

3.3.4 Free Fab Wax ™

FreeFAB aims to deliver a paradigm shift in the fabrication of moulds for precast concrete and GRC (Glass Reinforced Concrete). This shift is enabled by the pairing two technologies (3D printing & Milling) that each have particular advantages and inherent limitations can be negated by the other’s strengths. Specifically, it aims at significantly reducing the cost of producing a single mould for a single panel so that it is no longer prohibitively expensive and only possible for projects with excessive budgets.

This would present a unique opportunity within the construction sector, as bespoke and one-off elements can become a common feature on buildings, within interiors, on bridges, noise walls and for structural elements such as columns and beams. (Gardiner, Janssen & Kirchner 2016, 1-6.)

FreeFAB was developed by the Engineering Excellence Group Sydney – an innovation lab within Laing O'Rourke. Technologies incubated within this lab tailored to the needs of the company and the construction industry in general.

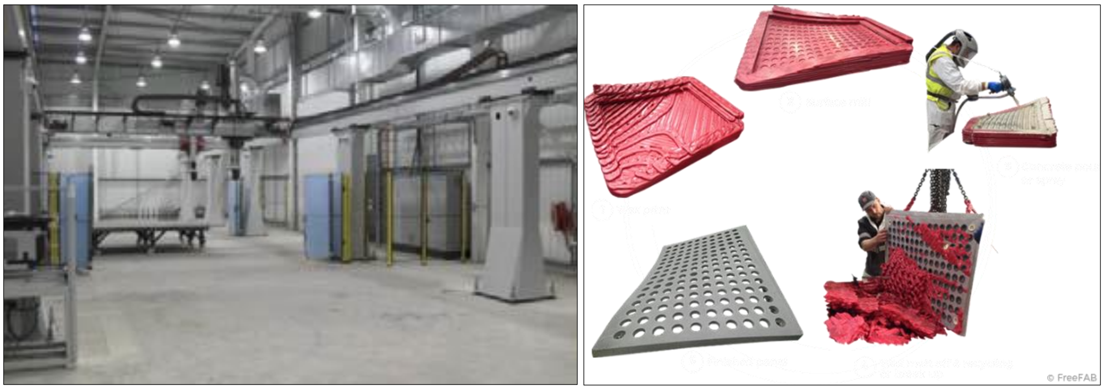
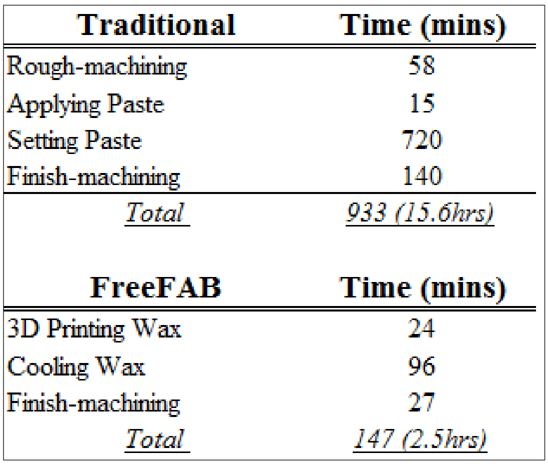


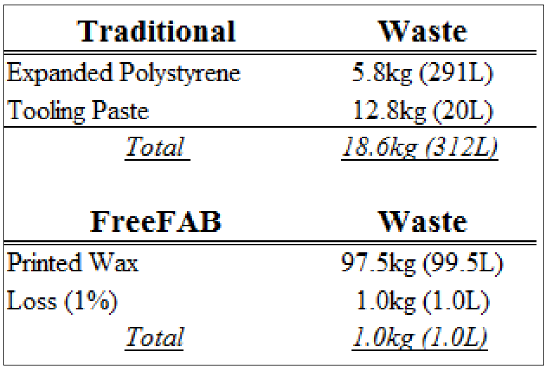
Figure 3. FreeFAB Wax gantry installed at GRC UK plant, UK. Image by Laing O'Rourke Ltd. (b) Conceptual illustration of FreeFAB process. Image by: FreeFab Wax^{TM}

Table 1. Fabrication Time Comparison



Traditional	**Time (mins)**
Rough-machining	58
Applying Paste	15
Setting Paste	720
Finish-machining	140
Total	*933 (15.6hrs)*
FreeFAB	**Time (mins)**
3D Printing Wax	24
Cooling Wax	96
Finish-machining	27
Total	*147 (2.5hrs)*

Table 2. Waste comparison



Traditional	**Waste**
Expanded Polystyrene	5.8kg (291L)
Tooling Paste	12.8kg (20L)
Total	*18.6kg (312L)*
FreeFAB	**Waste**
Printed Wax	97.5kg (99.5L)
Loss (1%)	1.0kg (1.0L)
Total	*1.0kg (1.0L)*

FreeFAB enables previously cost-prohibited design intentions to be achieved through its time, waste, and cost savings compared to traditional approaches. Further significant benefits lie in the use of the technology for projects that take advantage of the strengths of the technique in the production of highly bespoke buildings and infrastructure projects. (Gardiner, Janssen & Kirchner 2016, 1-6.)

3.3.5 BetAbram ™

Slovenian company BetAbram^{TM} has developed and is already selling a range of house printers that can 3D print habitable structures from a CAD file since August 2014. The three models available, P1, P2 and P3, can be delivered within two months of the ordering and finalizing payment. P1 will be 2000mm tall by 9000 mm wide by 16000 mm deep, weighing about 250kg (500kg with its rails). The P2 will measure 2000 mm x 6000 mm x 12000 mm and weigh about 200kg-400kg, while the P3 will measure 2000 mm x 3000 mm x 4000 mm and weigh P3-180kg-200kg. The largest one is the P1, which can print objects as long as 16 meters, with 9-meter width and 2-meter height. The machine can print layers of 25 cm. Prices start at €12,000 for the basic P3 model.
Though each model begins with a 2-meter height limit, the designers say the printer can be configured to build much larger structures.“Our vision is that we bring 3D houses to the people, ordinary people”. BetAbram^{TM} said. (Molitch-Hou 2014)

Picture 8. (a) BetAbramTM 3D printer P3 that prints 3000mm W x 4000mm L x 2000mm H and its weight is 180-200kg. Image by 3ders.com, BetAbramTM to release 3D house printer for12000 Euros in July/August 2014. (b) BetAbramTM is printing round stairs. Image by BetAbramTM team.

BetAbram^{TM} is a simple gantry based concrete extrusion 3D printer developed in Slovenia. The company has also stated that they use a concrete material mixed with additives for their printing process.3D printers require no wages and no rest periods, and can produce identical designs in a very short timeframe. (Molitch-Hou 2014)

3.3.6 MX3D

MX3D is a company that researches and develops groundbreaking robotic 3D printing technology. MX3D's robots print sustainable materials such as metals and synthetics in virtually any size or shape. Their engineers, craftsmen and software experts bring together digital technology, robotics and traditional industrial production. In 2014, MX3D invented an affordable multiple axis 3D printing tool. They equipped an industrial robot with an advanced welding machine and developed software to control it. MX3D can 3D print metals, and also resin in mid-air, without the need for support structures. (MX3D Team Bridge project 2017)

Now MX3D team is ready to 3D print the first fully functional steel bridge in the world over water in the center of Amsterdam to showcase their revolutionary technology and offer creative robotic manufacturing solutions that will transform Arts and Industry. (MX3D Team Bridge project 2017)

Picture 9. (a) Final design of metal bridge is started to print by MX3D in Amsterdam, the print will be ready early 2018. Image by MX3D. (b) In his lab in Amsterdam, Joris Laarman worked on the first drafts of the metal bridge. Image by: heijmans.nl

Printing a functional, life-size bridge is of course the ideal way to demonstrate the endless possibilities of this technique.

Since October 2015 this project officially kicked off by opening their workspace by Alderman and Deputy of Amsterdam, Mayor Kajsa Ollongren. She announced that the printed bridge will be installed across the Oudezijds Achterburgwal canal. (Fairs 2015)

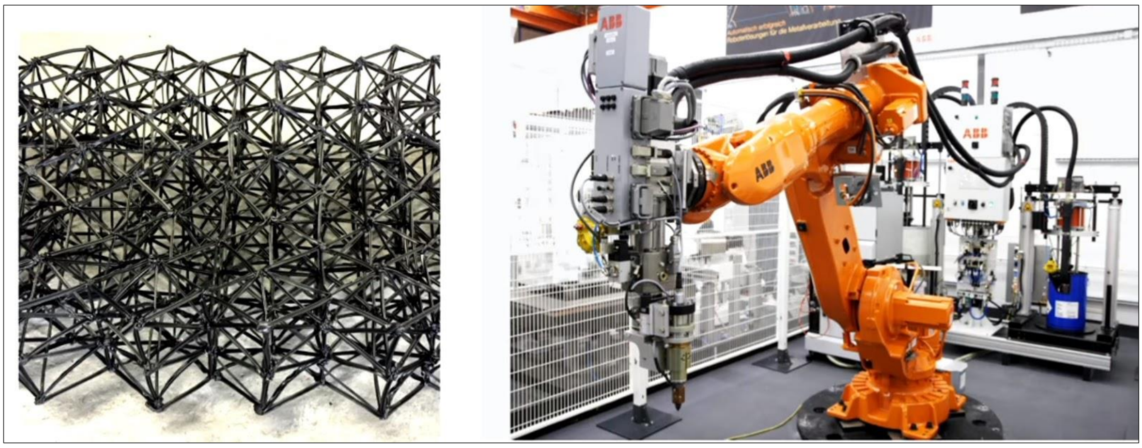
Research, development and improvement of the technology continuously, together with partners made this company the most innovative in hardware & software, construction and welding. The MX3D Bridge project would not exist without the support of partners, Autodesk, Heijmans, Arcelor Mittal, Air Liquide sponsors, ABB robotics, STV, Delcam, Within, Lenovo, public partners TU Delft, AMS, and Amsterdam City Council. (Fairs 2015)

3.3.7 Passive Dom

A new Ukrainian homebuilding startup called Passivdom uses a 3D-printing robot that can print parts for tiny houses. The machine can print the walls, roof, and floor of Passivdom's 35.3-square-meter model in about eight hours. The windows, doors, plumbing, and electrical systems are then added by human workers."We should have opportunities to live in nature away from civilization, but have comfortable conditions of a traditional house. This technology can allow us to live in the woods, on mountains, or on the shore far away from people and infrastructure," Sorokina says. (Garfield 2017)

To make a Passivdom home, the team maps out the plan for the 3D-printer in its factories in the Ukraine and California. Layer by layer, the seven-axel robot prints the roof, floor, and 20-cm-thick walls, which are made of carbon fibers, polyurethane, resins, basalt fibers, and fiberglass. When complete, the homes are completely autonomous and mobile, meaning they do not need to connect to external electrical and plumbing systems. Solar energy is stored in a battery connected to the houses, and water is collected and filtered from humidity in the air (or you can pour water into the system yourself). The houses also feature an independent sewage system. (Garfield 2017)

Depending on the model, the whole process can take under 24 hours. The design and production of larger houses with more specifications and finishes can take up to a month. If a house is pre-made, it can be shipped the next day. (Garfield 2017)



Picture 10. 3D-printed prefabricated frame for wall, roof and base. The printing materials include carbon fiber, fiberglass, polyurethane and resins. Image by: Julia Gerbut pitches PassivDom at Ecosummit Berlin 2017

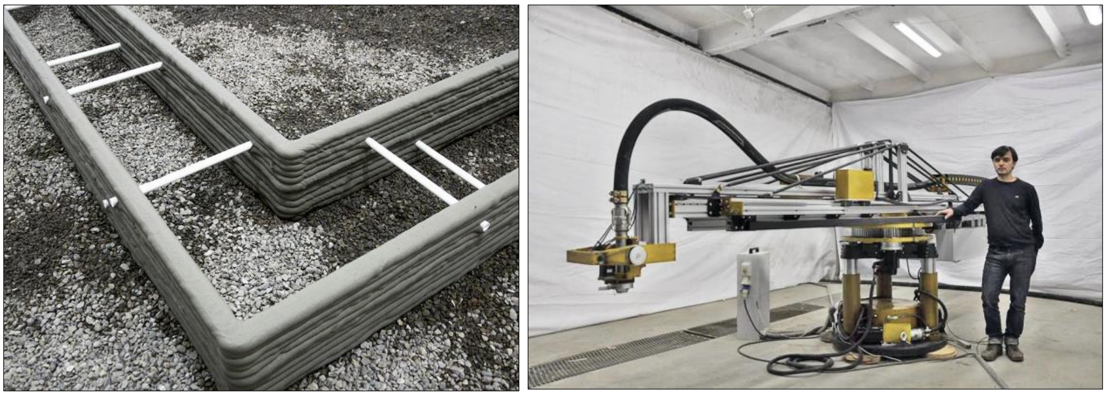
3D-printing is used for the production of the house frame. PassivDom creates the base of the future house, its walls, roof and fundamental platform. Factory produced modules, which can be assembled on a land within a day.

The startup believes 3D-printing is a cheaper, more efficient way to build homes that it can sell at a (relatively) affordable price. "Over 100 million people do not have a roof over their heads" Sorokina says. It is necessary to build more affordable houses.

Passivdom's homes, which start at $31,900, are now available for pre-order online in the Ukraine and the US, and the first ones will be delivered later this year. (Garfield 2017)

3.3.8 ApisCor

ApisCor is the developer company of unique mobile construction 3D printer that works in polar coordinates. Construction 3D printer ApisCor prints self-supporting walls and partitions, as well as permanent formwork for strip foundation and columns of reinforced Ferro-concrete framework. In future they plan to implement functions of inter-story floors and roof printing as well as automatic horizontal wall and foundation reinforcement placement. (Marks 2017)



Picture 11. (a) Framework for a building foundation by ApisCor printer. (b) Nikita Chen-yun-tai ApisCor inventor and ApisCor printer. Images by ApisCor

ApisCor 3D printer uses construction mix based on cement, which by its characteristics is similar to the concrete. These factors allow for its convenient transportation. Construction 3D printer ApisCor has relatively small dimensions: 4.5 meters long, 1.5 meters in height and width, weight 2 tons. Crane manipulator vehicle is used for their delivery to the construction site. The recommended number of stories of printed buildings 3-floors. (Marks 2017)

ApisCor 3D printer features:

- 1 mobile crane for printer transport
- 2 people required for operation control and material supply
- 8 KW of power consumed by operating printer
- 30 minutes required for installation and set-up
- 132 m² printing zone
- 0 kg construction waste
- Horizontal stabilization

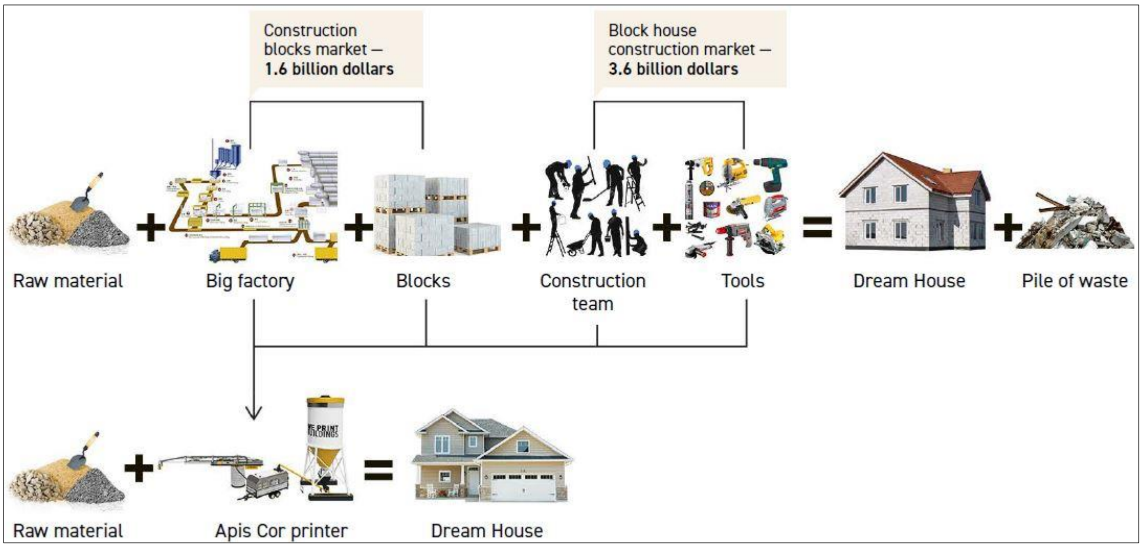


Figure 4. A comparison with conventional method of construction. Image by: ApisCor

As the printer prints self-bearing walls and partitions, it allows to save up to 70% on erecting building boxes compared to traditional construction techniques, such as with block method, because each block has to be put in place, cut to size and aligned. Also, there is the necessity to bring the required equipment and tools to the construction site, replace them after breakage, unload materials and oversee the builders. Often there is a risk of human error, and completion of a standard cottage house on average can take up to two months. (Marks 2017)

Nikita Chen-yun-tai, the inventor of the mobile printer and founder of “Apis Cor’ company says that he invented the 3D printer because of his desire to automate everything.
"We want to change public views that construction can't be fast, eco-friendly, efficient and reliable at the same time," says founder Nikita Chen-yun-tai. (Marks 2017)

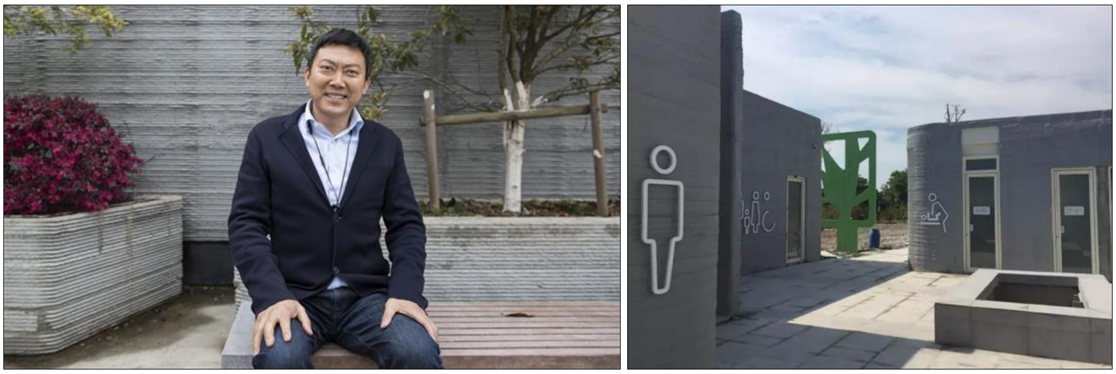
3.3.9 Winsun ™

Yingchuang (Winsun) is a high-tech enterprise who is engaged in the research and development of the new materials for construction. It currently owns more than 90 national patent certificates. Yingchuang (Winsun) is working on changing the way we construct buildings. Their focus has been and is still on creating new materials for construction and developing 3D printing construction machines. The vision is to make construction cheaper, faster and more environment friendly.

WinSun™ also used its 3D printing systems to make the parts for the drainage facility at Da Yang Mountain. This is not the first time it has worked with 3D printed drainage. However, as WinSun™ has been exploring the uses of 3D printing in many urban construction areas, including urban water supply, drainage, sanitation, landscaping, underground utilities, and ancillary facilities. (Tess 2016)

Picture 12. (a) Printed drainage by Winsun™ compare to (b) common way to drainage construction. Images by: 3ders.org, WinSun™ China unveils fully 3D printed public toilets in Suzhou, 2016.

WinSun also signed contracts with Winsun™ Global, is a joint venture consisting of Winsun™ and an American company. Over the next three years, they will set up factories in Saudi Arabia, the U.A.E, Qatar, Morocco, Tunisia and the United States and more than other 20 countries, in order to popularize 3D printing building. They also aim to especially for the Middle East and Africa to provide cheap and efficient homes for low-income families. (Clarke 2017)



Picture 13. (a) Ma Yihe Winsun™ known as Yingchuang Building Technique founder. (b) A 3D printed public toilet at China's Da Yang Mountain. Images by: 3ders.org, WinSun™ China unveils fully 3D printed public toilets in Suzhou, 2016.

The latest activities about the Winsun™ known as Yingchuang Building Technique is agreed with American engineering company (AECOM) to use the 3D printer in construction. With the three-year agreement, AECOM and WinSun™ intend to provide the 3D printing construction technology to clients across the globe. (Clarke 2017)

4 CAPABILITIES AND ADVANTAGES OF 3D PRINTING A HOUSE

One great advantage of 3D printing over traditional building techniques (such as prefabricated concrete) is the possibility of using a high level of detail and variation. Rather than using standardized elements, 3D printed designs can be modified and customized to fit the user’s needs and taste. It will no longer be more expensive or more labor intensive to add details for facade and it is easy to create unique objects. (Koslow, 2017)

3D printing is an additive manufacturing technique. That means the process goes straight from the raw material to the final product. There are no transport costs, as designs can simply be transferred digitally and printed locally. This also implies that when 3D printing is used widely in each part of the world, it will no longer be cheaper to have things produced in countries like China or Bangladesh as opposed to the i.e. Netherlands. Everyone can just produce everything in their own local context. (Koslow, 2017)

The top advantages of 3D printed houses and structures:

- Major potential for environmentally friendly construction projects. There are efforts to use the plethora of plastics floating in our oceans or lying around in waste dumps that could be used. Also, concrete and other materials can be better recycled and used more efficiently.
- Large-scale industrial 3D printing can be used to build inexpensive 3D printed houses in developing countries.
- Enables short construction periods, meaning simple 3D printed houses or shelters can be constructed quickly. This could be especially useful after an earthquake, a tornado, or another type of natural disaster.
- Construction 3D printing allows for the production shapes that are either impossible are too expensive with conventional methods.
- Otherworldly potential. NASA already has plans to use 3D printing for colonies on Mars. (Koslow, 2017)

Traditional construction processes take up a lot of time and labor costs. Due to engineering and preparation time the construction takes a longer time span than 3D Concrete printing. The final costs of 3D concrete printer are reduced and this can be up to 70% depending on the product. This cost-reduction is the result of factors like low labor costs and material costs. (CyBe construction advantages of 3D concrete printing 2017)

In addition 3D concrete printing enables new and other design possibilities. Giving architects more freedom in their design. Still there are many new design and engineering possibilities not yet being discovered and since the technology is being further developed new possibilities will take place.
When compared with conventional construction processes, the application of 3D printing techniques in concrete construction may offer excellent advantages including:

- Reduction of construction costs by eliminating formwork;
- Reduction of injury rates by eliminating dangerous jobs (e.g., working at heights), which would result in an increased level of safety in construction;
- Creation of high-end-technology-based jobs;
- Reduction of on-site construction time by operating at a constant rate;
- Minimizing the chance of errors by highly precise material deposition;

- Increasing sustainability in construction by reducing wastages of formwork,
- Increasing architectural freedom, which would enable more sophisticated designs for structural and aesthetic purposes;
- Enabling potential of multi functionality for structural/architectural elements by taking advantage of the complex geometry.(Nematollahi, Xia & Sanjayan 2017 1-8.)

4.1 Targets and future

4.1.1 Disasters

Natural disasters cause significant disruption to the lives of those affected by them. One of the major effects of natural disasters is the loss of housing. Additive manufacturing is a relatively new manufacturing technology that has advantages over traditional manufacturing. The potential of additive manufacturing for providing shelters after a natural disaster is appropriated. (Gregory, Hameedaldeen, Intumu, Spakousky, Toms & Steenhuis 2016)

The costs of providing shelters to victims of natural disasters is compared with traditional shelter options. It is found that the cost of 3D printed structures falls within the range of traditional shelter options. With continuing improvements in additive manufacturing technology as well as in terms of materials used, additive manufacturing may become an increasingly competitive option for disaster housing. (Gregory, Hameedaldeen, Intumu, Spakousky, Toms & Steenhuis 2016)

One of the major issues of concern after a large disaster is that of waste management. Earthquakes, hurricanes, floods, and tsunamis all have the potential to create huge amounts of destruction. Waste in the form of concrete, bricks, metal, and other materials must be removed from the disaster area. Some of the waste, such as bricks or steel, can be saved and reused in the post-disaster reconstruction.

Waste is also generated during the reconstruction phase after a disaster. However, this waste is usually more easily recyclable. While these are the ideal standards for post-disaster waste management, not all countries have the resources to deal with waste appropriately. One major problem is the non-availability of landfills for such a huge volume of waste left over by a massive destruction.

4.1.2 Energy consumption and waste

The Construction industry consumes much of the world's resources and produces approximately 30% of the world's waste. It is also the most inefficient of the world's high capital industries. The products of this industry (buildings) are also wasteful and inefficient.

If the way we build can be fundamentally changed, huge gains could be made toward reducing our demands on resources and the environment and help our society move toward a sustainable future.

The current rate of construction in China provides an alarming example where “more than one-half of China’s urban residential and commercial building stock in 2015 is to be constructed after the year 2000” (Zhu and Lin, 2004). When you consider this statistic in reference to a population of 1.3 billion people it is not difficult to realize that this is a global problem.

The UN climate change mitigation report states that for energy use “there is a global potential to reduce approximately 29% of the projected baseline emissions by 2020 cost effectively in the residential and commercial sectors, the highest among all sectors studied”. (Gardiner 2011, 154.)

It is estimated that the construction-demolition waste recovery rate is currently only around 30-35% (in addition to the quantity of excavated soil), thus, by 2020 the current rate should be at least doubled. The main needs in the field of C&D waste management where actions can serve the achievement of the 70% recovery rate by 2020 are listed below:

- Legislation has to be created to encourage the reuse and recovery of separated materials, to regulate treatment modalities and to set up a harmonized system of classification of secondary construction materials, road construction standards, technical guidelines, testing and rating methodologies have to be reviewed, and a

uniform system has to be set up to regulate the conditions of use of secondary materials. These will have to be February 2011 European Commission DG ENV Final Report Task 2 – Management of C&D waste 223 continuously developed in the future as new building practices and new types of building materials keep appearing which will require more complex techniques than current building materials.
- An efficient awareness raising campaign must be launched for the construction sector.
- Precise definitions must be accepted for the “end of waste aspect”.

Considering the relatively low current recycling rates, the high amounts of C&D waste illegally disposed of (and therefore not accounted for in the statistics reported), and the recent policy development specifically targeting C&D waste. However, one of the main challenges is still the better enforcement of existing legislation, particularly through diverting C&D waste from illegal landfill. Combined implementation and enforcement of landfill regulations and C&D waste targeted actions listed above will lead, at first, to better reporting and monitoring, and is likely to drive significant increases in recycling rates. (European Commission, Service contract on management of construction and demolition waste – sr1 Final Report Task 2, 222-223.)

Regarding to C&D waste producing, rather than investigate more about conventional construction structures to reduce C&D waste and energy consumption, additive manufacturing is huge revolution in this industry as earlier discussed and introduced experimental methods. (European Commission, Service contract on management of construction and demolition waste – sr1 Final Report Task 2, 222-223.)

4.1.3 Habitat in space

Permanent human habitation on a planetary body other than the Earth is one of science fiction's most common themes. As technology has advanced, and concerns about the future of humanity on Earth have increased, the argument that space colonization is an achievable and worthwhile goal has gained momentum. Because of its accessibility to Earth, the Moon and Mars have been seen as the most obvious natural expansion after Earth. ESA (European Space Agency) regards the moon as the next logical destination for humans beyond low earth orbit, and utilizing earth nearest neighbor should pave the way for human missions to Mars. (David 2016)

Engineers designed lunar habitats, London-based Foster + Partners architectural firm proposed a building construction with 3D-printer technology in January 2013 that would use lunar soil to produce Lunar building structures while using enclosed inflatable habitats for housing the human occupants inside the hard-shell lunar structures. Overall, these habitats would require only ten percent of the structure mass to be transported from Earth, while using local lunar materials for the other 90 percent of the structure mass. Printed lunar soil will provide both radiation and temperature insulation. Inside, a lightweight pressurized inflatable with the same dome shape will be the living environment for the first human Moon shelters. On Earth trial versions of this 3D-printing building technology are already printing 2 meters of building material per hour with the next-generation printers capable of 3.5 meters per hour, sufficient to complete a building in a week. (Diaz 2013)

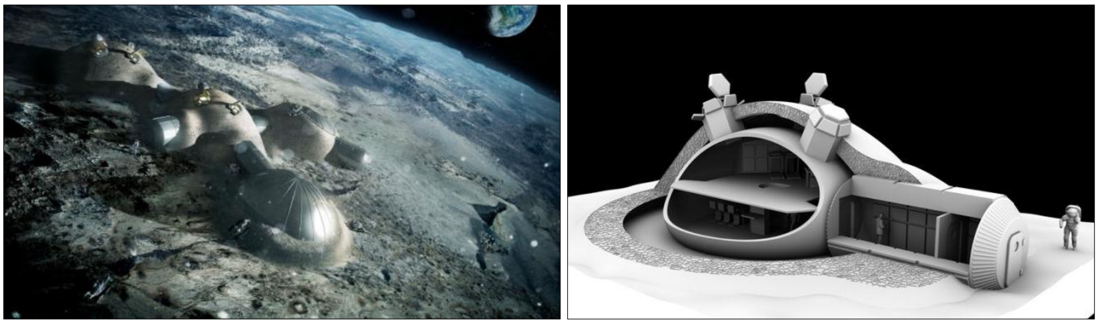


Figure 5. Foster + Partners is part of a consortium set up by the European Space Agency to explore the possibilities of 3D printing to construct lunar habitations. Addressing the challenges of transporting materials to the moon, the study is investigating the use of lunar soil, known as regolith, as building matter. Images by: ESA & Foster + Partners.

The potential of 3D printing with onsite materials on Mars is significant in that we may be able to build structures without bringing heavy equipment, supplies, materials, and structures from Earth. (Diaz 2013)

The 3D printed habitat Centennial Challenge is part of NASA’s space technology mission directorate to generate and develop ideas and practices for other world exploration.
Mars has become a particular area of focus for a range of space programs. Seeing actual, 3D-printed objects for this phase makes the goals of this challenge more conceivable than ever. This is the first step toward building an entire habitat structure, and the potential to use this technology to aid human exploration to new worlds is thrilling. (Harbaugh 2017)

Picture 14. The Foster + Partners | Branch Technology team from Chattanooga, Tennessee, with their 3D-printed dome structure after it was strength tested Aug. 26, 2017, at Caterpillar Inc.'s Edwards Demonstration and Learning Center in Peoria, Illinois. The team won first place and $250,000 at Phase 2: Level 3 of NASA’s 3D-Printed Habitat Challenge. Image by: NASA/Joel Kowsky

4.1.4 Construction sustainability and ecology

Construction sustainability presents significant challenges for the construction industry worldwide. The construction sustainability of construction 3D printing has been identified as a characteristic of the additive nature of construction 3D printing, by potentially using less materials and producing less waste than subtractive and formative fabrication techniques. However, it has also been argued that the construction sustainability of a construction 3D printing technique must consider further attributes, such as material, energy use, air, water, biodiversity and human factors. Therefore, the construction sustainability of construction 3D printing needs to be considered based on the assessment of individual techniques rather than construction 3D printing as a single body. (Gardiner 2011, 352.)

The design and operation of new buildings as integrated systems has been identified as one method by which energy use could be reduced by 75%. An important method by which such reductions in energy use could be achieved was identified as the adoption and implementation of ‘passive design’ principles. (Gardiner 2011, 353.)

Construction 3D printing techniques have been identified as having a potential advantage over conventional construction techniques due to their ability to fabricate elements with a level of control that allows for detailed arrangement of materials that can be designed in such a way to passively respond to specific environmental conditions of a building. This capability is obviously dependent on the responsiveness of the design and digital definition from the construction 3D printing bases its fabrication. (Gardiner 2011, 353.)

For explanation of this terminology ‘sustainable construction’ will considered and apply to the following components:

- Material use: raw and processed material inputs throughout the life of the building, sustainability of the resource, waste, recyclability.
- Energy use: embodied energy of raw and processed materials, sustainability of the resource, fabrication of the building, operation of the building, decommissioning, and capture of energy from the environment.
- Air: pollution, recycling.
- Water: use, collection, waste and recycling.
- Biodiversity: support and improvement of flora and fauna

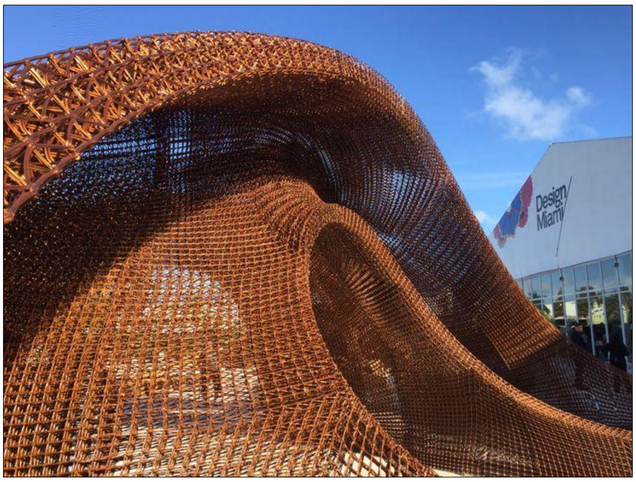
- Human factors: functional, thermal, acoustic, sunlight access, ventilation. (Gardiner 2011, 49.)

Reference to many of the items in the above listing will not be possible in this explanation, but should serve as a guide to further consideration of the sustainability of construction, in reference to construction 3D printing. Construction 3D printing techniques are considered well suited to take advantage of virtual prototyping, analysis and optimization techniques, due to their complete dependence on numerical data for deposition.
The aim of this approach to form a new ecological system, on earth, that brings man back into harmony with the natural world and break down the barriers between man, technology and nature. This minimal architecture is a response to what Otto has discovered and observed from the study of organic and inorganic systems and in ‘primitive architecture, where no material is used to excess and where decoration makes sense if essential’. (Gardiner 2011, 116.)

4.1.5 Architectural concept

Sometimes conventional construction creativity, flexibility, its full potentialities and design inspiration are challenging to build, but eventually 3D printers capabilities have evolved at those challenges.
A 3D printer can be proven a valuable tool to construct more innovative designs that push the limits and architectural design into parametric, biometric, organic and generative designs. There is possibility to add more of the complex forms observed in nature and apply it to structural building shapes. Approaching to the design and shapes that have been impossible and consuming the time to build by hand is one gain of 3D printing uses in construction industry. (Platonics ltd 2017)

3D printing technology has developed to a degree where building has become easier and faster than ever. Traditional architectural designs are great for some specific situations such as early conceptualization stages, design study or fine arts collection. But in the commercial demand for hand-drawn architectural design has declined as computer generated renderings replace traditional hand-drawing design skills. 3D digital architectural or High-end digital computer graphics and virtual images lead architectural designs into an exciting future. (Platonics ltd 2017)



Picture 15. Printed example of architectural structure design by branch Technology Company. Image by: branch technology.

Every day, computer generated techniques rise up new versions of software or applications. Complex 3D modeling software are used to create three-dimensional images and designs which let viewers see the proposed building from 360 degrees and the environment around the building before it is built.

3D construction models provide an affordable high quality of architectural designs to know much more about your building designs. A construction 3D printable architectural design can provide visualization effort, effectively integrated, reliable design and essentially the design which is out of human hands to build. (Platonics ltd 2017)

3D modelling has seen huge changes with the aid of computers (CAD), and is largely concerned with the attractiveness of a building; what size should the building be (height, width, depth etc.) in what ratios should the windows be to the size of the wall, what material should the building be built in, given the desired shape. One of the beautiful things about 3D printers is that they do not detect difficulties between simple and complex forms, and point is: to let the printer take care of producing elements. Regarding those benefits, 3D printing can prove a valuable tool that both saves your time and elevates your creativity. (Platonics ltd 2017)

4.2 Concrete 3D printing

Most useable material on our planet in construction industry is concrete and to form the concrete in construction, formworks are significant and necessary. But the amount of waste from formworks generally is not environmentally friendly. In addition, in conventional methods of construction formwork freedom to build various geometries has limitations and costs much. Also the speed of construction challenges, material production, transportation, labor intensity, safety issues, and manufacturing formwork in-situ and each step is time consuming. (Nematollahi, Xia & Sanjayan 2017 1-8.)

Last but not least, the conventional concrete mixture can be determined as a material in the main methods of additive manufacturing construction industry which are:

- Extrusion based
- Powder based

A conventional mixture of concrete which contains a typical proportion of coarse aggregate will not be adequate for additive construction applications because of insufficient flow through a nozzle apparatus. To allow for adequate flow, the concrete material must include a large proportion of fine materials such as sand, but it can still incorporate a significant content of coarse aggregate which is expected to reduce shrinkage. (Nematollahi, Xia & Sanjayan 2017 1-8.)

Chemical admixtures and additives appeared to have varying degrees of success in aiding flow and shape stability. The addition of fly ash provided the best improvement in flow, while the addition of bentonite provided the best shape stability. The use of chemical admixtures significantly increased fluidity of the mixture, but its use should be accounted for by reducing the water content of the mixture in the future. (Rushing, Al-Chaar, Eick, Burroughs, Shannon, Barna & Case 2017)

Moreover, the concrete formulation desired properties in extrusion based method can be identified as follow:

- Flow in the fresh state must be sufficient to allow pumping and extrusion through a narrow nozzle.
- Slump must be minimal to allow for shape stability after extrusion

- The coarse aggregate size must be small to minimize the possibility of clogging during extrusion.
- Early properties, notably setting time, must be controlled to allow each layer of construction to support subsequent layers. (Rushing, Al-Chaar, Eick, Burroughs, Shannon, Barna & Case 2017)

However, these properties will be changed depending on the mix design, the technique method and the deposition device. The material hardened properties may also be affected by the process.

4.3 Financial aspects

The 3D concrete printing market size is estimated to grow from USD 24.5 Million in 2015 to USD 56.4 Million by 2021, at a CAGR (Compound annual growth rate) of 15.02%. 3D concrete printing is transforming the construction industry as it is a less expensive process, fast, accurate, and offers affordable housing solutions. Lower material usage and lower labor costs create a less expensive construction method. The estimation of market size, future growth and potential of 3D concrete printing market is based on the product type, concrete type, software, end-use, and region. (Marketsandmarkets, 3D Concrete Printing market by product type, concrete type, by Software end-use sector & by Region – Forecast 2016)

The base year considered is 2015 and the market size is forecasted from 2016 to 2021. With the rise in industrialization, the construction sector is expected to play a key role in fueling the growth of the 3D concrete printing market in the next five years.
(Marketsandmarkets, 3D Concrete Printing market by product type, concrete type, by Software end-use sector & by Region – Forecast 2016)

Implementation of this technology may be initially complicated by prevailing policies that regulate labor, zoning, and land costs. Nevertheless, the availability of this new technology has the potential to change the building industry in the world. For instance, it can be the solution to homelessness, and an emergency solution when the “big one” comes. The impact of the Contour Crafting technology will be significant, given the current US

construction-related expenditures which total $300 billion in the public sector and $700 billion in the for-profit sector, annually.
(Contour crafting. Offering Automated Construction of Various Types of Structures 2017)

5 RESTRICTIONS AND COMPLEXITIES

In terms of disadvantages, it is obviously a huge challenge to create a building that complies with all the current building requirements. There is the question of insulation, fireproofing, wind loads, foundations and such. These are cases, that as well as the possible materials to print, have to be researched and investigated. (3d print canal house. What are some of the advantages and disadvantages of 3D printing a building 2017)

Currently, the 3D printing a building would present a set of huge technological and economic challenges. Automation of various parts and products has evolved considerably in the last two decades, but construction remains largely as a manual practice. This is because the various conventional methods of manufacturing automation do not lend themselves to construction of large structures. (Khoshnevis & Bekey 2002, 1-6.)

Developing Construction 3D printing techniques is not merely a matter of scaling up existing rapid prototyping techniques. “A key point is that as you increase the build scale, the volume flow of material will force the design of a new process: it cannot simply be scaled up”. (Gardiner 2011, 95.)

5.1 Automation in construction is incredibly slow

It is already possible to print 3D printed multilayer buildings. While 3D printing techniques have been successfully applied in a wide range of industries, such as aerospace and automotive, its application in concrete construction industry is still in its infancy. The progress in the development of printers is not sufficient and that causes a huge gap between architectural ideas and manufacturing. There are still many barriers on the road to reach printed houses that can satisfy all the required living standards. (Khoshnevis & Bekey 2002, 1-6.)

The prospect of additive manufacturing is positive. It might be able to completely change the conventional construction industry if the printers get developed so that both the monetary and time investment in printing become justifiable. (Khoshnevis & Bekey 2002, 1-6.)

Implementation of automation in the construction territories has been slow due to:

- unsuitability of the available automated fabrication technologies for large scale products
- conventional design approaches that are not suitable for automation
- significantly smaller ratio of production quantity/type of final products as compared with other industries
- limitations in the materials that could be employed by an automated system
- economic unattractiveness of expensive automated equipment
- Managerial issues.

(Khoshnevis & Bekey 2002, 1-6.)

5.2 Construction productivity problem

Seven percent of world’s working age population are employed in the construction company and it is one of the biggest players in the world economy with $10 trillion related cost of goods and services every year. (Barbosa, Woetzel, Mischke, Ribeirinho, Sridhar, Parsons, Bertram & Brown. 2017)

Poor productivity in construction industry today is the result of multi sector players. Regulation is complex and in many countries, there is a high level of unregistered construction companies and sometimes corruption. Conventional operations are not efficient enough or based on today’s technologies. Technologies in other industries adopted decades ago which now are coming or spreading to the construction sectors. Performance management, talent development, standard processes, technology improvements and integration between those procedures are priorities to get higher rate of productivity. (Woetzel, Sridhar & Mischke, 2017)

Construction companies mostly resist to changes and transformations because of operational cultures which includes all executive challenges. If the companies start to shift the fundamental changes that are necessary, for instance resource utilization and adaption to new technologies rather than company’s profit, then they are in the winning position. Adapting new technologies enhance productivity innovation is tried by some companies but most of them have difficulty to change because of conventional systems, unique requirements for budgets, planning and operation. (Blanco, Janauskas & Ribeirinho. 2016)

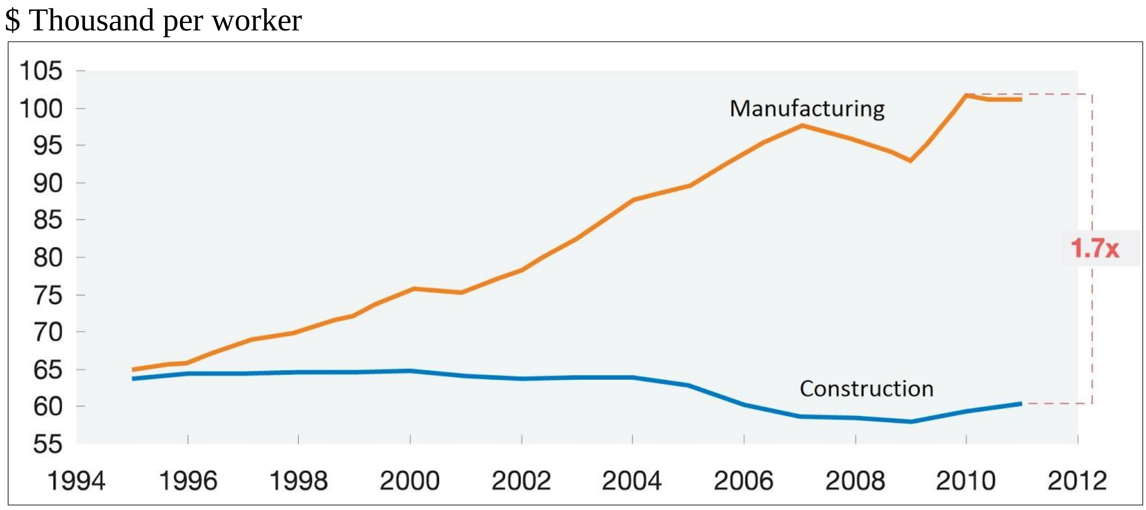


Figure 6. Overview of productivity improvement over time. Productivity in manufacturing has nearly doubled, whereas in construction remained flat. Source countries: Belgium, France, Germany, Italy, Spain, United Kingdom, United states. World input-output Database. Researched by: McKinsey & Company.

Integration between different players such as owner, designer, contractor, QA and safety expert is apparently a problem. Many subcontractors have own contracts without any overall management. Construction companies generally would like that subcontractors take most of the risks of collaboration. (Blanco, Janauskas & Ribeirinho. 2016)

It is efficient to integrate new technologies such as robotic methods which is including the construction 3D printing. Production risk rate will be too low; however, other manufacturers today are updated by new technologies.

5.3 Workflow management

The main idea in additive manufacturing is to manage the workflows from architectural design to the automated or printing execution processes on site. The goal of this procedure is low rate of error and mistakes by the printers or robots that is the aim in additive manufacturing or automation. (Bock 1998, 37-45.)

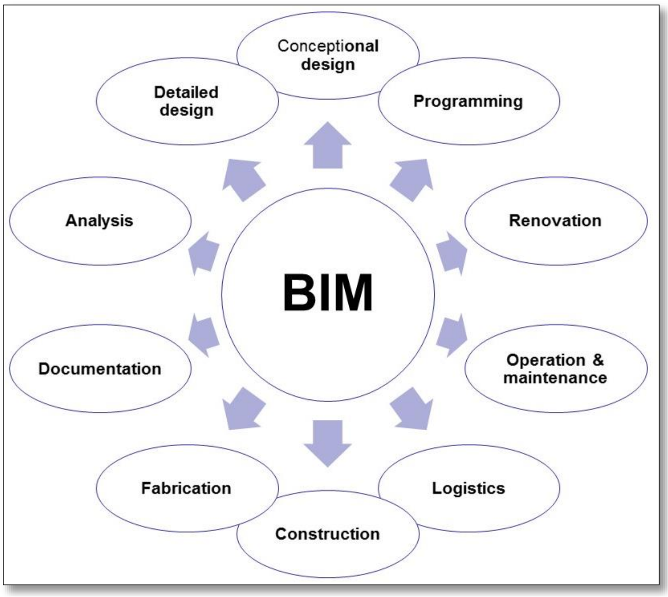


Figure 7. The construction industry has already been adapting to the digital revolution with Building Information Modeling (BIM) and smart technologies.

The complexity of the construction processes by technological and advanced construction methods must be integrated. In this process also architects, engineers and all other players in construction project must be adapted. Taking the places step by step in these processes to the respective result is necessary. (Bock 1998, 37-45.) Based on concrete printing which is the main technique in construction additive manufacturing, one of the workflow challenges is CNC programming language which creates a standard software to generate

G-code for each layer of the build and print or non-printable paths. Concrete printing aims significant approach to save time in simulation about 30 percent. For instance, other problems to manage the printing workflow are:

- Over deposited material under manufacturing
- Stop/start of nozzle movement
- Tuning the machine parameters
- Critical mechanical property in the extrusion

The result in practical works well if extrusion of data preparation works continuously. (Lim, Buswell, LE, Austin, Gibb & Thorpe 2012)

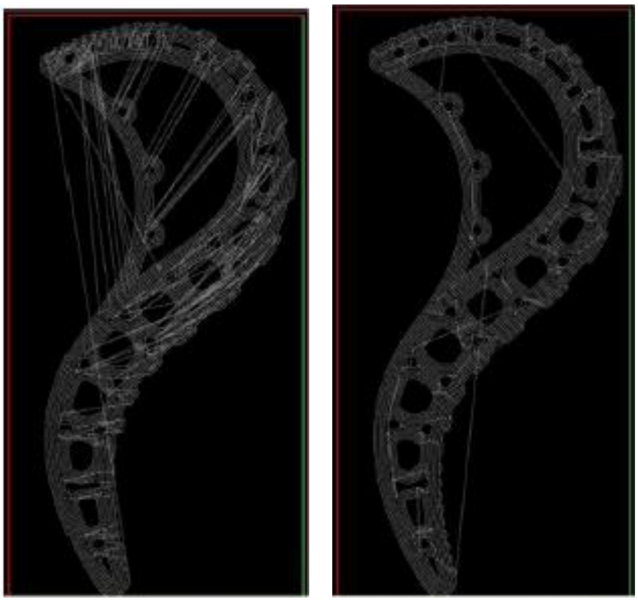


Figure 8. Comparison of printing time between non- optimized and optimized printing paths using a CNC simulator. Image: Lim, Buswell, LE, Austin, Gibb & Thorpe, Developments in construction-scale additive manufacturing processes, 2012.

5.4 Approach to habitability

As discussed earlier, construction automation, new technologies adaptation and productivity is slow and poor now. Problems still exist in large scale of world construction territories because of inhabitability of the buildings that are built using 3D printers.
The buildings' living standards and safety rates for printed houses are under question. Are they habitable? Norms and cultures of building habitable houses are extremely strong. Changing those may take the construction industry a decade or even more.

Construction is a huge industry, which consists of many sectors. Digital information and integration which is called Building Information Modelling (BIM) provides a large unit that includes all construction sectors. In addition, BIM provides new technologies to make habitable, smart future buildings and increased productivity.

6 CONCLUSION

The construction industry, not known for its speed of evolving. But it has been adapting to the digital revolution with Building Information Modeling (BIM) and smart technologies, alongside a stronger commitment to leaner and greener construction.
Technology of 3D printing is still young and presents lot of limitations, but there are high expectations and hopes for the future of 3D printed buildings and building components.

Creating the buildings with complicated shapes may become one of the biggest advantages for most architects. Their imagination will be able to defeat previous obstacles related to limitation of traditional techniques of building.

3D printing may transform modern architecture, nevertheless, this technique should be developed taking into consideration sustainability issues both for material selection and construction method. There are numerous advantages coming from developing 3D technology in construction and most important ones could be resumed as:

- Lower costs – the cost of printing construction elements of houses is much lower than traditional construction methods, also material transportation and storage on sites is limited.
- Environmental friendly construction processes and the use of raw materials with low embodied energy (i.e. construction and industrial wastes).
- Reduced number of injuries and fatalities onsite as the printers will be able to do most hazardous and dangerous works.
- Wet construction processes are minimized, so that building erection process generate less material wastes and dust compared to traditional methods.
- Time savings – time required to complete the building can be considerably reduced.

Today we have access to highly advanced technologies. However, our social and economic system has not kept up with our technological capabilities that could easily create a world of abundance. The goal of this thesis is briefly to solve the huge manual challenges in construction industry that we have today.

7 FUTURE RESEARCH OPPORTUNITIES

This research is intended to form a foundation for a larger investigation that will likely grow up around construction 3D printing. It is expected that new technologies enquiry will grow significantly in the near future as the capabilities of the existing machines increase and in parallel new techniques are invented.

8 REFERENCES

3D print canal house. 2017. What are some of the advantages and disadvantages of 3D printing a building? http://3dprintcanalhouse.com/frequently-asked-questions-2. 2017.

Barbosa, F. Woetzel, J. Mischke, J. Ribeirinho, M. J. Sridhar, M. Parsons, M. Bertram, N & Brown, S. 2017. Reinventing construction through a productivity revolution. McKinsey & Company is a global management consulting firm. http://bit.ly/2mz9SBr. February, 2017.

Blanco, J L. Janauskas, M & Ribeirinho, M J. 2016. Beating the low-productivity trap: How to transform construction operations. McKinsey & Company is a global management consulting firm. http://bit.ly/2odfll5. July, 2016.

Bock, T. Automation and robotics in building construction. 1998. 15th International Symposium on Automation and Robotics in Construction (ISARC), Munich, Germany. April, pp. 37-45. 1998.

Clarke, C. 2017. AECOM forms agreement with WinSun to use 3D printing in construction. 3D printing industry. https://3dprintingindustry.com/news/aecom-forms-agreement-winsun-use-3d-printing-construction-113608. 18.05.2017. May, 2017.

Contour crafting.2017. Offering Automated Construction of Various Types of Structures. http://contourcrafting.com/building-construction. 2017.

Cousineau, L & Nobuyasu, M. 1998. Construction robots the search for new building technology in Japan. Chicago Institute & Kokushikan University. United State of America. The American Society of Civil Engineering. 1998.

CyBe construction. 2017. What are the advantages of 3D concrete printing in comparison with traditional construction method? Amsterdam. https://www.cybe.eu/frequently-asked-questions. 2017.

David, L. 2016. Europe Aiming for International 'Moon Village'. Space.com's Space Insider Columnist. April 26, 2016.

Diaz, J. 2013. This is what lunar base could really look like. Www.gizmodo.com. January 31, 2013.

Dini, E. 2013. Large Scale 3D Printing: Enrico Dini at TEDxBocconiU. Https: //youtu.be/L65QKBDQ6mc. May 21, 2013.

Dutt D'Cunha, S. 2017.This Startup Is Disrupting the Construction Industry with 3D-Printing Robots. https://www.forbes.com/sites/suparna-dutt/2017/06/14/this-startup-is-ready-with-3d-printing-robots-to-build-your-house-fast-and-cheap. Jun, 2017.

European Commission (DG ENV).Final Report Task 2. 2011. Service contract on management of construction and demolition waste – sr1. A project under the Framework contract ENV.G.4/FRA/2008/0112. February, 2011.

Fairs, M. 2015. Joris Laarman's canal bridge in Amsterdam could take 3D printing to a higher level. https://www.dezeen.com/2015/10/19/joris-laarman-3d-printed-canal-bridge-Amsterdam, October 19, 2015.

Frearson, A. 2016. DUS Architects builds 3D-printed micro home in Amsterdam. https://www.dezeen.com/2016/08/30/dus-architects-3d-printed-micro-home-amsterdam-cabin-bathtub. August 30, 2016.

Gardiner, J, B. Janssen, S & Kirchner, N. 2016. A realization of a construction scale robotic system for 3D printing of complex formwork. 33rd International Symposium on Automation and Robotics in Construction. Laing O'Rourke Engineering Excellence Group, Chippendale, Australia.

Gardiner, J.B. 2011. Exploring the Emerging Design Territory of Construction 3D Printing – Project Led Architectural Research. RMIT University. School of Architecture and Design. Design and Social Context Portfolio. August 2011.

Garfield, L. 2017. A robot can print this $32,000 house in as little as eight hours. http://nordic.businessinsider.com/3d-printed-house-robot-passivdom-2017-4. Apr, 2017.

Gregory, M1. Hameedaldeen, S. A1. Intumu, L. M1. Spakousky, J. J1. Toms, J. B1 & Steenhuis, H. J2. 3D Printing and Disaster Shelter Costs. 2016. 1Eastern Washington University, Spokane, WA - USA & 2Hawaii Pacific University, Honolulu, HI - USA. September, 2016.

Harbaugh, J. 2017. NASA Awards $100,000 in First Printing Stage of 3D-Printed Habitat Challenge. NASA Gov. https://go.nasa.gov/2k0McsL. August 4, 2017.

Khoshnevis, B. Bekey, G. 2002. Automated Construction using Contour Crafting Applications on Earth and beyond. University of Southern California. Industrial & Systems Engineering. Computer Science.pp.1-6. September 23, 2002.

Koslow, T. World's 35 greatest 3D Printed Structures. 2017. https://all3dp.com/1/3d-printed-house-homes-buildings-3d-printing-construction. Jun 22, 2017.

Lim, S. Buswell, R, A. LE, T, T. Austin, S, A. Gibb, A, G, F & Thorpe, S. Developments in construction-scale additive manufacturing processes. 2012. Submitted to Automation in Construction. PP. 262, 268. 2012.

Maeda, J. 1994. Development and Application of the SMART System. Automation and Robotics in Construction XI, Proceeding of the 11th International symposium on automation and robotics in construction (ISARC) Brighton. pp. 457-464. 1994.

Market and markets. 2016. 3D Concrete Printing Market By Product Type (Walls, Floors & Roofs, Panels & Lintels), by Concrete Type (Ready-Mix, High-Density, Precast, Shotcrete), by Software (Design, Inspection, Printing), by End-Use Sector (Architectural, Industrial, Domestic) & by Region - Forecast to 2021. http://www.marketsandmarkets.com/Market-Reports/3d-concrete-printing-market-10362292.html. May, 2016.

Marks, G. 2017. This startup will 3D print your house for $10K http://wapo.st/2nbfKQB?tid=ss_tw&utm_term=.b4a75907edf2. Mar, 2017.

Molitch-Hou, M. 2014. More Emerges about the First Manufacturer of 3D House Printers. https://3dprintingindustry.com/news/emerges-first-manufacturer-3d-house-printers-38801. Dec, 2014.

MX3D team. 2017. Bridge project. Amsterdam. http://mx3d.com/projects/bridge-2. 2015-2017.

Nematollahi, B. Xia, M & Sanjayan, J. Current Progress of 3D Concrete Printing Technologies. 2017. 34th International Symposium on Automation and Robotics in Construction. 2017.

Platonics, 2017, can 3D printing boost your architectural creativity? https://blog.platonics.fi/can-3d-printing-can-boost-your-architectural-creativity-a039427350e1, June 20, 2017.

Rushing, T, S. Al-Chaar, G. Eick, B, A. Burroughs, J. Shannon, J. Barna, L & Case, M. 2017. Investigation of concrete mixtures for additive construction. Rapid Prototyping Journal, Vol. 23 Issue: 1, pp.74-80. 2017.

Saunders, S. 2017. CyBe Construction Announces That 3D Printing is Complete for Dubai's R & Drone Laboratory. https://3dprint.com/176561/cybe-3d-printed-dubai-laboratory. Jun, 2017.

Tess. 2016. WinSun China unveils fully 3D printed public toilets in Suzhou. 3ders. http://www.3ders.org/articles/20160901-winsun-china-unveils-fully-3d-printed-public-toilets-at-da-yang-mountain-suzhou.html. September 01, 2016.

Woetzel, J. Sridhar, M. Mischke, J. 2017. The construction industry has a productivity problem and here’s how to solve it. http://on.mktw.net/2mR4VEg. March 6, 2017.

Xiao, E., 2016. Meet the 19-year-old high school dropout who wants to 3D print cities. https://www.techinasia.com/cazza-launch-asia-middle-east. November, 2016.

Zhu, Y. & Lin, B. 2004. Sustainable housing and urban construction in China. Energy and Buildings, 36, 1287-1297.