3D Printing of Buildings. Limits, Design, Advantages and Disadvantages. Could This Technique Contribute to Sustainability of Future Buildings?

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Abstract. Recently, a phenomenon of "printing" houses and construction 3D printers has taken on or greatly increased in many parts of the world. This phenomenon is intensively shown in various media and in science news and science articles. 3D printers and house printing are praised to be very advantageous from economical, energetic and sustainable point of view. However, there are no norms or rules to cover this type of construction works. In addition, a lack of methods for structural calculation and for certification of materials regarding "printing" is observed. Effects on future design and execution of this type of constructions on the market labor and on education in construction domain are unknown. In addition to some practical applications and their characteristics, this paper tries to present the requirements of 3D-Printing applications in the field of constructions, limitation of current technologies, the advantages and disadvantages of 3D printed houses and the effects on the listed above sub-domains. Future of 3D printing for constructions is analyzed in a sustainability perspective.

Keywords: 3D printing · Buildings · Sustainability

1 Introduction

During the last years, in media as in professional literature, news and scientific articles about 3D printers and 3D printed houses often appear. 3D printing technology emerged in 1980s [1], when the Japanese Dr. Hideo Kodama had requested a patent on a device for rapid prototyping (RP). This patent had never been issued, however.

In 1986, a first invention patent is received by Charles (Chuck) Hull, the co-founder of 3D Systems Corporation, one of the largest and most prosperous of today's 3D printing organization. In 1987, Hull created a first 3D printer named SLA-1 and sold it in 1988. For a view on the topic beginnings, Table 1 [1] shows a short history of 3D printing. *Additive fabrication*, *additive processes*, *additive techniques*, *additive layer manufacturing*, *layer manufacturing*, and *freeform fabrication* are some synonyms for AM. This process is

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based on virtual model data created in CAD software in order to obtain objects or parts. Organizations are trying to watch the field in order to regulate it. Conforming to the ISO/ASTM 52921:2013 [2] international standard, “Printing 3D” or “Additive Manufacturing – AM” is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods.

Table 1. A history of 3D printing beginnings [1].

Year	Achievement
1980	First patent application for RP technology, filled by Dr. Kodama, in Japan
1986	The first patent - to Charles Hull for stereolithography apparatus (SLA)
1987	SLA-1, introduced
1989	SLS (selective laser sintering) patent issued to Carl Deckard
1990	EOS company sold its first “Stereos” system
1992	FDM (Fused Deposition Modelling) patent issued to Stratasys
1996	Sanders Prototype (later Solidscape) and ZCorporation were set up
1997	Arcam was established
1998	Object Geometries launched
2000	MCP Technologies introduced the SLM technology
2002	EnvisionTec was founded
2004	Dr. Bowyer - RepRap concept of open source, self-replicating 3D printer
2005	ExOne - spin-off from the Extrude Hone Corporation
2007	The first system under $10.000 from 3D Systems
2008	Desktop Factory was acquired by 3D Systems
2009	The first commercially available 3D printer – in a kit form, based on the RepRap concept
2012	Alternative 3D printing processes introduced at the entry level on the market
2013	Stratasys acquires Makerboot

Additionally, according to ISO/ASTM standards [3], AM can be divided in seven process categories according to the techniques used to create those layers (Fig. 1).

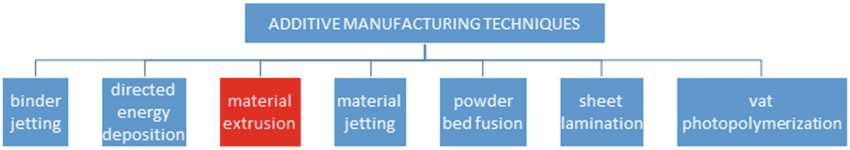

Fig. 1. Additive manufacturing techniques [3].

For constructions, from the seven process categories pertaining to 3D printing shown in Fig. 1, the 3D printing extruding material technology is used (for concrete, steel, clay etc.). This method is often named Fused Deposition Modelling (FDM) and sometimes, Fused Filament Fabrication (FFF). Fused Deposition Modelling, or FDM, technology is the most used on the global level. Conforming to statistics from July 2018 [4], this technology is used in 69% of cases (Fig. 2).

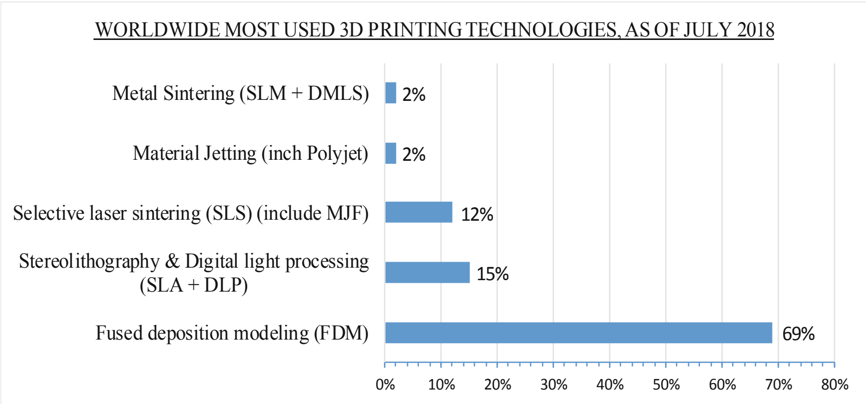

Fig. 2. Worldwide most used 3D printing technologies, as of July 2018 [4]. SLM = Selective Laser Melting; DMLS = Direct Metal Selective Sintering; SLS = Selective Laser Sintering; MJF = Multi-Jet Fusion; SLA = Stereo-Lithography Apparatus; DLP = Digital Light Processing; FDM = Fused Deposition Modeling

The FDM 3D printing technology for constructions had been invented in 1989 by Scott Crump, the American co-founder of the Californian Stratasys company, a relevant actor in the field. Finally, in 1992, the brevet for FDM was issued to Stratasys marking the start of an intensive development in 3D technologies. It is worthy to remember that Medicine is one of the first domain to adopt the FDM technology, in early 1990s.

2 Goal and Methodology in 3D Printing Analysis

The goal of this research is to establish the role (as a component of sustainability) and the extent of the phenomenon, the need for actual use, the possibility of future use, directions of development and any other professional observations that could be withdrawn. These elements should be wrapped up in series of advantages and disadvantages that must be in the views professionals involved or willing to be involved into this field.

Due to relative novelty of the field and for achieving the goal, the paper uses a mostly intuitive, analytic and critic way to conduct the research based on a series of representative examples of applications worldwide. The analysis is trying to observe the difference between the common, classical way, of building and the new means, devices and realizations. In addition, it should be underlined what could be the benefits for the actual requirements of our society in the context of smart cities, sustainability playing a key place. Therefore, the results of this stage in research of 3D printing for Civil Engineering domain is mainly general and qualitative. Remarks and observations are opening the way to quantitative and normative studies when the field approaches maturity.

3 3D Printed Constructions. Examples

In order to get a critical view on the 3D technology in constructions field, it is relevant to show some important practical applications and the year they emerged, as follows. Some data about each application, considered significant, is presented. In addition, a large diversity of construction types, country of applications, methods, materials, designers is implying the scale of the interest for 3D printing in construction field. Of course, the number of real 3D buildings and bridges is already very large.

The examples that follow might be named already as "classical" and became very fast well known for professionals. They are useful for this paper because they offer the frame for a critical view on 3D printing in construction domain.

2013 - "Grotto I" - The 9th Architecture Exhibition, Archilab, France
One of the first use of a 3D printed constructions, dated back in 2013, might be considered the architects/programmers' Michael Hansmeyer and Benjamin Dillenburger creation exposed to the French Archilab Exhibition [5, 6]. It is named *Grotto Prototype*, or *Digital Grotesque I*, and represents an immersive space at human scale, totally built from 3D printed sandstone (and a second *Grotto* was made in 2017). A resolution of 0.3 mm on each layer, or 300 dpi, a height of 3.2 m, a surface of 16 m^2 and a weight of 5.8 tones are some very impressive characteristics of this piece of art. In order to facilitate the transportation and assembling of *Grotto I*, a modular blocks system had been developed. Each block is about 80 by 120 cm and it is weighting around 100 kg. The virtual model had 260 millions individual surfaces, 42 billion vortexes and needed 78 GB to be digitally stored. The digital design lasted for one year, printing – one months, and assembling – one day (Fig. 3). Michael Hansmeyer had created this *Grotto* under the concept of *Computational Architecture*.

Fig. 3. Grotto I [5, 6]

2014 - "Project EGG" - The Netherlands
"Project EGG" [6, 7] is conceived by the Dutch architect Michiel van der Kley. The project is composed from 4760 of unique "stones" and was presented at Dutch Design Week in Eindhoven in 2014. Some users of 3D printers from different parts of the world helped printing the 4760 pieces and sent them to be assembled in The Netherlands. The contributors had obtained the STL file and used it. STL is a file format native for the stereolithography CAD software and it was created by 3D Systems in 1987. The "Project EGG" is 4.88 by 3.96 by 3.05 m in size (Fig. 4a).

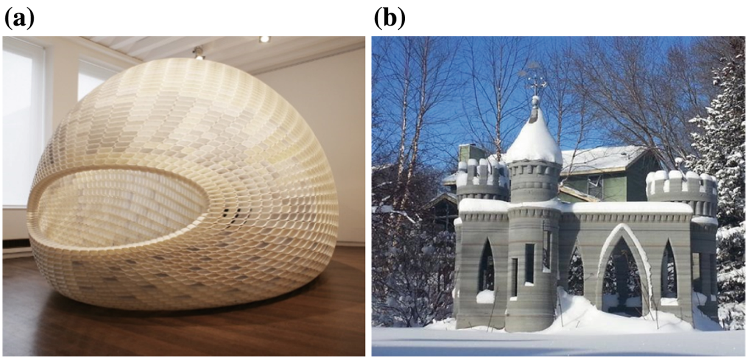

Fig. 4. a - "Project EGG" - The Netherland [6, 7]; b - "First 3D Printed Castle" - USA [6, 8]

2014 - "First 3D Printed Castle" - USA
"First 3D Printed Castle" [6, 8] was printed by Andrey Rudenko. This construction is made from printed concrete layers with 10 mm thickness by 30 mm width. Construction's total dimensions are 3 by 5 by 4–6 m (Fig. 4b).

2014 - "Apartment Building in China" - China
"Apartment Building in China" [6, 9] is a construction realized in Chinese province of Jiangsu by Winsun company. The walls and other structural elements had been 3D printed outside the construction site.

For walls' printing, a so called "ink", made from constructions' waste and a bonding agent, was used. Finally, a high thermal and structural resistance had been achieved. The 3D printed building is supposed to resist well to earthquakes.

According to Winsun, compared to traditional construction method, some of the new method achievements are: the material costs is reduced by 60%, the work force costs is reduced by 80% and the building time is reduced by 70% (Fig. 5a).

2015 - "MX3D Bridge" - The Netherlands
"MX3D Bridge" [6, 10] is a metallic bridge designed by the Dutch Joris Laarman in 2015 and finally printed in 2018. Robot arms attached to the structure were used for

(a) (b)

Fig. 5. a - “Apartment Building in China” - China [6, 9]; b - “MX3D Bridge” - The Netherlands [6, 10]

printing. A special characteristic of this system is that it can be used in relatively narrow spaces (Fig. 5b).

2015 - “Philippines Hotel” - Philippines

The “Philippines Hotel” [6, 8] – is a 130 m^2 of Lewis Grand Hotel in Philippines. It includes 3D printed bedrooms, living room and Jacuzzi bathroom. The owner, Lewis Yakich together with the Russian born Andrey Rudenko were the main designers. For the printing, sand and volcanic ashes were used. After 100 h printing, strong walls had been realized (Fig. 6a).

(a) (b)

Fig. 6. a. “Philippines Hotel” - Philippines [6, 8]; b. “Office Building” - U A E [6, 9]

2015 - “Office Building” - United Arab Emirates

The Office Building [6, 9], was designed by Thornton Tomasetti and Syska Hennessy from Gensler architecture company for the National Committee of United Arab Emirates. The building is the headquarters of Dubai Futures Foundation and is 240 m^2. 3D printed pieces of the building had been made by Winsun company from China, in Shanghai. The printing lasted for 17 days in China and, assembled in two days in Dubai (Fig. 6b).

2016 - "Apis Cor" - Russia
"Apis Cor" [6, 11] - is a 38 m^2 house printed *in situ*. It is using a mixture of solid elements an liquid polyurethane. The main observation in this case is that the *in situ* printing had reduced transportation and assembling costs (Fig. 7a).

(a) (b)

Fig. 7. a - "Apis Cor" - Russia [6, 11]; b - "Villa in China" - China [6, 12].

2016 - "Villa in China" – China
"Villa in China" [6, 12]. This is a 400 m^2 house conceived by the Chinese company named HuaShang Tengda. The walls are 25 cm thick made from C30 concrete. It is estimated that this 3D printed construction would resist to an 8 Richter Local Magnitude major earthquake (Fig. 7b).

2017 - "Pedestrian Bridge in Madrid" - Spain
"Pedestrian Bridge in Madrid" [6, 13] - is a bridge designed by Catalunya Advanced Architecture Institute and printed by ACCIONA, a company specialized on infrastructure and renewable energy. The length of the bridge is 12 m while the width is 1.75 m. It is using concrete reinforced by microfibers (Fig. 8a).

2017 - "Bicycle Bridge" - The Netherlands
"Bicycle Bridge", [6, 14], is designed mainly by the Technical University of Eindhoven in collaboration with BAM company from United Kingdom. It is 3D printed and it is destined for bicycle users. The bridge is made from pre-tensioned reinforced concrete. This bridge was initially 3D printed in 8 individual parts, each 3.5 m width and then assembled. The concrete used in this case is a non-shrinkable one (Fig. 8b).

2018 - "Gaia, a 3D Printed House with Earth" - Italy
"**Gaia**" [6, 15] - is low-cost house that is only 12 m^2 surface, conceived by the Italian engineer Alberto Chiusoli, and 3D printed using Crane WASP technology.

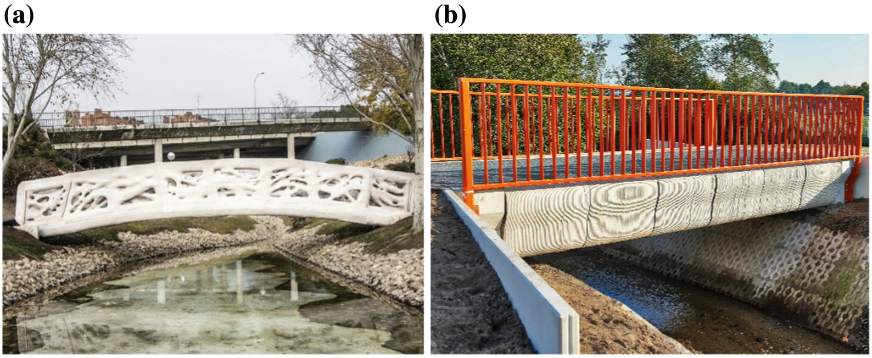

Fig. 8. a - "Pedestrian Bridge in Madrid" - Spain [6, 13]; b - "Bicycle Bridge" - Technical University in Eindhoven & BAM [6, 14]

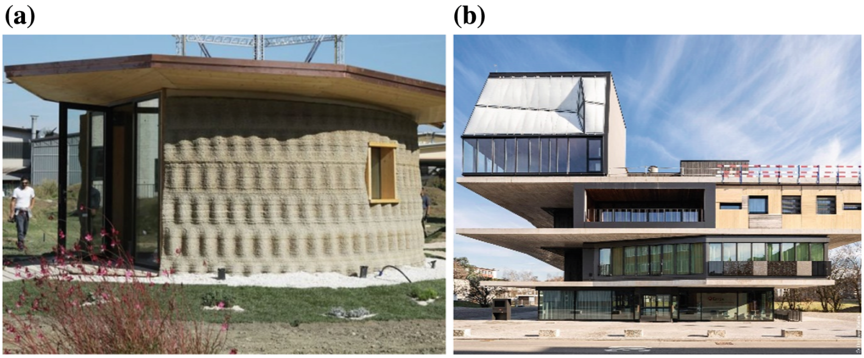

Fig. 9. a - "Gaia" - Italy [6, 15]; b - "DFAB House" - Switzerland [6, 16].

A natural material had been used, a mixture from brut soil and natural wastes of rice crops. This way, the house is becoming ecological and sustainable (see Fig. 9a).

2019 - "DFAB House" - Switzerland

"DFAB House" [6, 16] - is realized by ETH Zurich's researches and professors in collaboration with industrial partners using 3D printers and robots. It has three floors and is based on NEST (Next Evolution in Sustainable Building Technologies) system. It has a surface of 200 m^2. It is considered the first inhabited digitally planned and build construction (see Fig. 9b).

4 Advantages and Disadvantages of 3D Printing in Constructions

Analyzing the methods, real examples, materials, concepts, opinions of professionals, some advantages and disadvantages of 3D printing for constructions had been observed, especially when compared to the classical ones.

On one hand, advantages that emerged after the above analysis are:

- rapidity of construction building compared to classical methods
- reduction of material use due to printed advantageous shapes (a goal of sustainability)
- reduction of wood/steel used for forms and scaffolding (in many cases they are no longer needed) – also a goal of sustainability
- reduced costs of constructions, compared to classical constructions
- 3D printing in construction no longer needs design drawing for forms or reinforcement
- possibility of recycled materials use (goal of sustainability)
- execution details with high precision, improving architecture and strength
- possibility of building constructions parts or objects even in narrow spaces (goal of sustainability through more rational use of space)
- 3D printing of complex constructions shapes within a reduced cost range
- substantial reduction of manpower cost in building
- reduced waste quantity resulted from constructions' building (sustainability goal)
- fuel consumption reduction and assembling time reduction in the case of *in situ* 3D printing. It implies also a reduction in toxic gases coming from constructions machineries and, this way, it is combating the global warming (goal of sustainability)
- dramatic decrease in work and traffic accidents involving construction domain
- repeatability of design, projects and multiple use of the same devices (3D printers) implying reduced costs for social houses and for after-disaster shelters. Conforming [17], "Not only could this (3D printing) revolutionize the construction industry, but the less expensive process could also affect housing affordability"
- integration with BIM related design and technologies [18] (goal of sustainability).

On the other hand, disadvantages that emerged after the above analysis are:

- relatively high price of 3D printers-devices (starting from $250,000 and above)
- the cvasi-impossibility of simultaneous use of more than one material
- 3D printing software and programming may be very expensive
- structural computation for 3D printed constructions is cumbersome, complex and need to be developed
- materials (like concrete) cannot be vibrated, in order to eliminate voids
- irregular shapes of walls resulted from 3D printing, due to layers
- limited height of 3D printed constructions (at least for the moment)
- loosing of work places not only in constructions domain but also in adjacent connected fields of activities
- unknown, yet, consequences of damaged or faulted 3D printers usage
- insufficient information on sustainability of (some) 3D printed constructions
- insufficient information on strength of (some) 3D printed constructions
- work temperature of 3D printing processes must be positive, above freezing point
- possibility of disastrous cyberattacks on 3D printers software or hardware
- insufficient information on long term behavior of 3D printed walls, in case of performing holes throughout them for installing pipes and cables
- a possible monopolist market if 3D printing of constructions is concentrated in a few companies

- impossibility of use or reduced use of low skilled labor force, that could (apparently) lead to higher costs or lack of high shilled manpower
- lack of design, building and verification codes for 3D printed constructions
- lack of formation and training for skilled workers in 3D printing technology field
- high costs due to patented inventions and projects
- lack of scientific studies and researches, technical references that are enough advanced that could reduce and limit the above presented disadvantages
- strong increase of energy consumption (electricity) for 3D printers functioning, even 100 times more than the classical construction methods, conforming [19].

5 Conclusions. Future of 3D Printing for Constructions

This paper shows a brief history and examples of 3D printing in construction field. A list of advantages and disadvantages is demonstrating the stage of development in this topic. Acting in amplifying advantages and reducing the disadvantages is leading to a great progress.

Use of 3D printing in constructions domain generates a strong emulation in the field. If, for the moment, mass use of 3D printing in civil and industrial constructions field is not yet seen, certainly it has a very favorable near future in prefabricated construction industry. Appearance of 3D printers simultaneously using more materials, robotization of (prefabricated) parts assembling and other technologies will unavoidable lead to cvasi-complete constructions (embedding concrete, reinforcement, finishing, electrical cables, pipes and so on) with very advantageous production costs not only for investors but for beneficiaries, too. A consequence will be a drastic reduction in the lack of shelters for pour population in many parts of the world leading to a better resilience of our society. Another consequence will be a more sustainable construction domain, [20], that will be environmental friendly and combating global warming.

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