3D Printing in Architecture: One Step Closer to a Sustainable Built Environment

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Abstract. Sustainability has become a very popular term in many disciplines and investors/researchers devote a considerable amount of time and money for related studies to define their policies as well as initiatives on this subject. Today CAD/CAM technologies propose a wide range of concepts and implementation that support the concept of sustainability. Recent studies show that, developing computational technologies and 3D printers have potential to change the way we built our environment. From this respect this paper evaluates the use 3D printers in construction through recently built pioneering examples from the sustainability point of view. Results indicate that the special features of the 3D printing process, such as faster and precise construction, reduced labour costs and construction waste etc. these technologies offer a revolutionary approach in terms of sustainability.

Keywords: Computational design · CAD/CAM · 3D printing
Architectural technology · Waste materials

1 Introduction: Digital Design and Manufacturing Paradigm in Architecture

> …Digital technologies are changing architectural practices in a way that few were able to anticipate just a decade ago…
>
> Branko Kolarevic [1]

This century has become prominent with two main concepts in architecture; the first one is sustainability in architecture which has been seeking for a less environmental footprint in the ecosystem and the second is digital technologies that drive a novel approach in all kinds of man made products including architecture [2]. The use of computer aided design (CAD) in architecture has been extended from being a medium of representation to a media of design and manufacturing [1, 3].

Being aware of potentials/transformations in design and manufacturing process and their effects on form/structure and material usage, provide 21st century's designers with new horizons. Especially the concepts and premise applications of parametric design, adaptive design, nanomaterials, Building Information Modeling (BIM), 3D printing and robotics have potentials to radically change the design and the construction processes [4, 5] so the language and identity of 21st century architecture. There is no doubt

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that, CAD/CAM applications have been rapidly changing the conventional architectural design and construction processes since the end of the last century. In this process researchers and practitioners have been seeking for new tectonics and materials which reveals the beauty of using cutting edge technology in a "sustainable" point of view.

In this context, it is possible to argue that, through cutting-edge building technologies, innovative construction materials/methods and better decision-making systems, not only projects are getting smarter but also it is an opportunity to built our environment more sustainable. When the recent concepts and developments in construction are considered it is seen that a number of construction trends shaping the industry. A word cloud is prepared and illustrated in Fig. 1. From this perspective it is possible to claim that, through "computational models", which are the inseparable part of a design anymore, not only all stages of design can be controlled but also manufacturing and management can be achieved.

Fig. 1. Abstract word cloud for construction trends shaping the industry (drawn by the authors)

It is seen that among these trends 3D printers are becoming rapidly spread. Causing a drastic change/transformation in several disciplines has also being experienced in the field of architecture. Their usage in architecture have shifted from producing scale modeling to a full scale end-product [6]. "The potential of using mock-ups as the end product" is one of the most important changes that we encounter in the field of construction of architecture [7]. From this context this papers discusses the shifting practice of 3D prints in architecture with an emphasis on the potential use of recycled material in construction.

2 3D Printing as a Multi-faceted Technology in Manufacturing

> …3D printing technology has the potential to revolutionize the way we make almost everything…
>
> Barack Obama [8]

3D printing or additive manufacturing (AM) is a process of making 3D objects getting all related information from 3D solid models. In an additive process an object is created by laying down successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object [9].

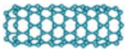
The main principle of 3D printing is “stereolithography”, outlined by Charles Hull, in a 1984 patent, as “a system for generating three-dimensional objects by making a cross-sectional pattern of the object to be formed” [10]. It is a process that solidifies thin layers of ultraviolet (UV) light sensitive liquid polymer using a laser. After that, Selective Laser Sintering (SLS) and Fused Deposition Modelling (FDM) Technologies (1988) [11] were the milestones of its development. The evolution of 3D printing technology continues to improve in the speed of processing, the complexity of design, and the variety of materials used. Over the last decade they started to be used in everyday life. According to Hager [12] thanks to the open source systems, prototyping of new product, and innovative applications of 3D printing in various fields are available for everyone. 3D printing technology is cited among a list of 12 potentially economically disruptive technologies in a report by McKinsey Global Institute [13]. They argue that the technologies they mentioned have potential to affect billions of consumers, hundreds of millions of workers, and trillions of dollars of economic activity across industries [13] (Table 1).

Table 1. Economically disruptive technologies [13]

	Mobile internet	Increasingly inexpensive and capable mobile computing devices and Internet connectivity
	Automation of knowledge work	Intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments
	The internet of things	Networks of low-cost sensors and actuators for data collection, monitoring, decision making, and process optimization
	Cloud technology	Use of computer hardware and software resources delivered over a network or the Internet, often as a service
	Advanced robotics	Increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans

(*continued*)

Table 1. (*continued*)

	Autonomous and near-autonomous vehicles	Vehicles that can navigate and operate with reduced or no human intervention
	Next-generation genomics	Fast, low-cost gene sequencing, advanced big data analytics, and synthetic biology ("writing" DNA)
	Energy storage	Devices or systems that store energy for later use, including batteries
	3D printing	Additive manufacturing techniques to create objects by printing layers of material based on digital models
	Advanced materials	Materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality
	Advanced oil and gas exploration and recovery	Exploration and recovery techniques that make extraction of unconventional oil and gas economical
	Renewable energy	Generation of electricity from renewable sources with reduced harmful climate impact

As Kamath [14] states the "effortless transition from digital to physical" is made possible by digital fabrication technology which can create a physical artifact from a 3D digital file [14]. The reason why 3D printers are very common in all kinds of industrial fields today is obvious because there are distinct advantages that this technology presents. Figure 2 presents the percentages of the disciplines that range from motor vehicles to medicine, from academic works to many other. Furthermore, several annually evaluations release that regarding the current demands, markets for 3D printing are expected to grow rapidly. Such that, according to Wohlers Report 2014, the worldwide 3D printing industry is now expected to grow from \$3.07B in revenue in 2013 to \$12.8B by 2018, and exceed \$21B in worldwide revenue by 2020 [15] (Fig. 3). Wohlers Report 2013 had forecast the industry would grow to become a \$10.8B industry by 2021. If 3DP applications grow rapidly in the next 10 years questions may arise about the sustainability of 3D printing manufacturing processes. Therefore, research into the sustainability of 3DP needs to be performed before the markets explode, so adjustments can be made at an early stage [16].

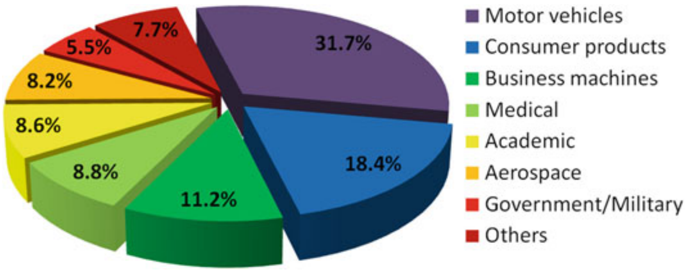


Fig. 2. The range of 3D printing usage according to disciplines [17]

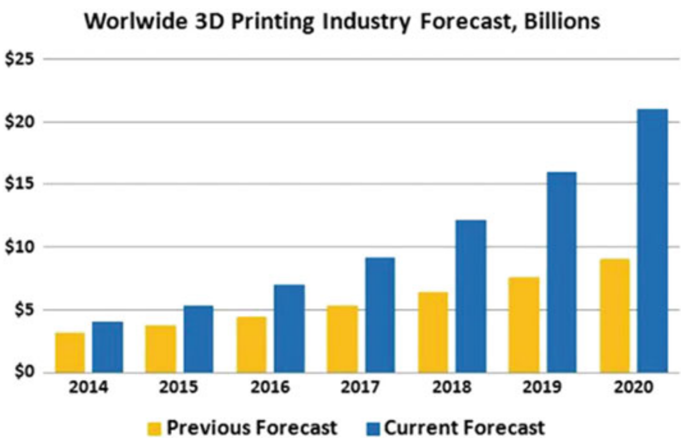


Fig. 3. The worldwide 3D printing industry forecast [18]

Today, among the advantages of using 3D printers in all industries can be listed as follows [19];

- Affordable customization,
- Allows manufacture of more efficient designs; lighter, stronger, less assembly required,
- One machine, unlimited product lines,
- Very small objects (even nano),
- Efficient use of raw materials (less waste),
- Pay by weight; complexity is free,
- Batches of one, created on demand,
- Print at point of assembly/consumption,
- Manufacturing accessible to all; lower entry barriers,
- New supply chain and retail opportunities.

CSC Leading Edge Forum report (2012) highlights that, the following areas need further development [19];

- Printing large volumes economically
- Expanding the range of printable materials
- Reducing the cost of printable materials
- Using multiple materials in the same printer, including those for printing electronics
- Printing very large objects
- Improving durability and quality

Furthermore, Gebler et al. [16] argues that 3D printing technology represents a relative novel technology in manufacturing which is associated with potentially strong stimuli for “sustainable development”. Many other researches show that 3D printing is an industrial manufacturing process with the potential to reduce resources and energy demands as significantly well as process-related CO_2 emissions per unit of gross domestic product [20–23].

Contrary to conventional manufacturing subtractive processes, 3D printing performs additive means of production. From this aspect, 3D printers are able to manufacture with a wide variety of different material types, that are supplied in different states (powder, filament, pellets, granules, resin etc.). Table 2 shows 3D printing types that uses different materials. This means all kind of recyclable materials such as, glass, plastic, thermoplastic polymers (ABS), metals, ceramics etc. can be shape during a printing process. Moreover, 3D printing reduces manufacturing-related resource inputs because it only requires the amount of material which ends up in the printed good without too many losses [24]. Support materials can usually be reused [25].

Table 2. 3D printing technology type and materials [26]

Classification	Technology	Description	Materials	Developers (Country)
Binder jetting	3D printing Ink-jetting S-print M-print	Creates objects by depositing a binding agent to join powdered material	Metal, polymer, ceramic	ExOne (US) Voxljet (Germany) 3D Systems (US)
Direct energy deposition	Direct metal deposition Laser deposition Laser consolidation Electron beam direct melting	Builds parts by using focused thermal energy to fuse materials as they are deposited on a substrate	Metal: powder and wire	DM3D (US) NRC-IMI (Canada) Irepa Laser (France) Trumpf (Germany) Sciaky (US)
Material extrusion	Fused deposition modeling	Creates objects by dispensing material through a nozzle to build layers	Polymer	Stratasys (US) Delta Micro Factory (China) 3D Systems (US)

(*continued*)

Table 2. (*continued*)

Classification	Technology	Description	Materials	Developers (Country)
Material jetting	Polyjet lnk-jetting Thermojet	Builds parts by depositing small droplets of build material, which are then cured by exposure to light	Photopolymer, wax	Stratasys (US) LUXeXcel (Netherlands) 3D Systems (US)
Powder bed fusion	Direct metal laser sintering Selective laser melting Electron beam melting Selective laser sintering	Creates objects by using thermal energy to fuse regions of a powder bed	Metal, polymer, ceramic	EOS (Germany) Renishaw (UK) Phenix Systems (France) Matsuura Machinery (Japan) AROAM (Sweden) 3D Systems (US)
Sheet lamination	Ultrasonic consolidation Laminated object manufacture	Builds parts by trimming sheets of material and binding them together in layers	Hybrids. metallic, ceramic	Fabrisonic (US) CAM-LEM (US)
VAT photopolymerisation	Stereolithography Digital light processing	Builds parts by using light to selectively cure layers of material in a vat of photopolymer	Photopolymer, ceramic	3D Systems (US) EnvisionTEC (Germany) DWS Sri (Italy) Lithoz (Austria)

3 3D Printing: An Opportunity to Construct by Using Recycled Materials

In the construction industry, 3D printers are used to create 3D models, prototypes or small, non-structural building components such as landscaping bricks or decorative elements [28]. This technology enabled architects to create scale models faster and economical, in all phase of the design. 3d printers provide architects with better visualization, optimization through tests such as wind, sound, stability etc. applied on scaled models and form finding research during the design process.

3D models of London City Hall designed by Foster and Partners can be given as one of the best examples revealing the power of printing technologies during the form finding process (Fig. 4). Especially the concept of seamless production, file to factory and real time behavior in architecture [29] that 3D printers offer architects resulted in an innovative way of using these technologies; from scale model to the end product.

Fig. 4. 3D models of London City Hall [27]

Within this context the following examples are selected to discuss how 3D printing technologies can transform the way we are going to built in the near future. Particularly, improvement of the printing materials and 3D technology became to be the goal for many companies all over the world from all industry sectors. In 2014, real revolution in construction industry has started, as the first house was printed starting a new chapter in building technology.

3.1 The ETFE Plastic Roof Canopy of the 6 Bevis Marks Building, England

A decorative steel sheath is developed for a canopy on the roof of the refurbished 6 Bevis Marks office building in central London. Priestman, the architect of the project, claims that this is the world's first 3D-printed component for a specific use in the construction industry. The parts serve as complex joints between the building's columns and the arms of its canopy [30]. It's architectural in so far as it's been through an approval process and tried/tested, and actually installed in a building [31] (Fig. 5).

Fig. 5. Sheath for a canopy [30, 31]

According to the Munn [32] most materials can be recycled and it is possible to recycle 100% of steel and aluminium. Recycling reduces the embodied energy of steel by 72% and aluminium by 95%. From this respect due to their ability to use all type of molten metal, 3D printers have potentials to provide sustainability in construction.

3.2 3D Printed Houses, China

Winsun New Materials company's a materials firm in China has developed a way to print 10 houses in a day [33]. A special 3D printer that produces a layered combination of discarded construction materials and cement is an important example to show this technology can be use for recycling. According to Oberti [34], each building is constructed from 3D printed walls and foundations, while the roofs are made of metal construction. As Bartolacci [35] reports, printing each structure costing under $5,000 and a single setting can produce almost four buildings at the same time with very little human labor is required.

The elements of each building are printed in a factory, and then transported on site for assembly. In many of China's cities, where development has been focused on show-stopping mega projects and towering skyscrapers, the country's population continues to urbanize at a rapid rate [36].

To conclude, these efficient and inexpensive system could help the increasing demand for efficient, affordable housing with its pioneering system that has the potential to change the way we building the mass housing (Fig. 6).

Fig. 6. 3D printed house from waste concrete [34, 35]

3.3 3D Canal House, Netherlands

The 3D Print Canal House is research project in Amsterdam, performed by DUS Architects, studying the possibilities of 3D printing in architecture [37]. The aim of the projects is to create a 13 room demonstration house. A special 3D printer called "KamerMaker" was installed inside a shipping container near the Canal [38]. The house is made of many printed elements. Each element showcases a research update in shape, structure and material. The project shows that architecture can be catalyst for cross-sectoral innovation. It is collectively funded by all partners, who contribute to the project with knowledge and financial means [38] (Fig. 7).

Fig. 7. General view of the project [38]

The printer creates wall components from a bioplastic mix of plastic fibres and 80% plant oil. Wall components are then interlocked together and filled with bio-concrete to provide structural strength [39]. It is important to note that all the materials used in the project are recyclable. As an entrepreneurial building project, the canal hose ha a potential to revolutionize the building industry and offer new tailor made housing solutions worldwide [38, 39] (Figs. 8, 9 and 10).

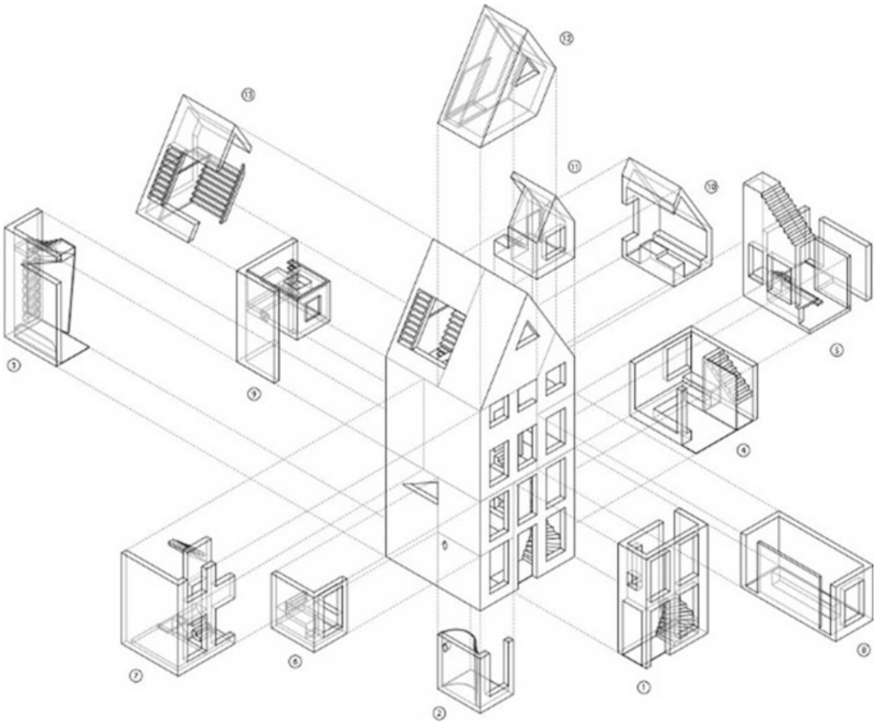


Fig. 8. Decomposition of the model [40]

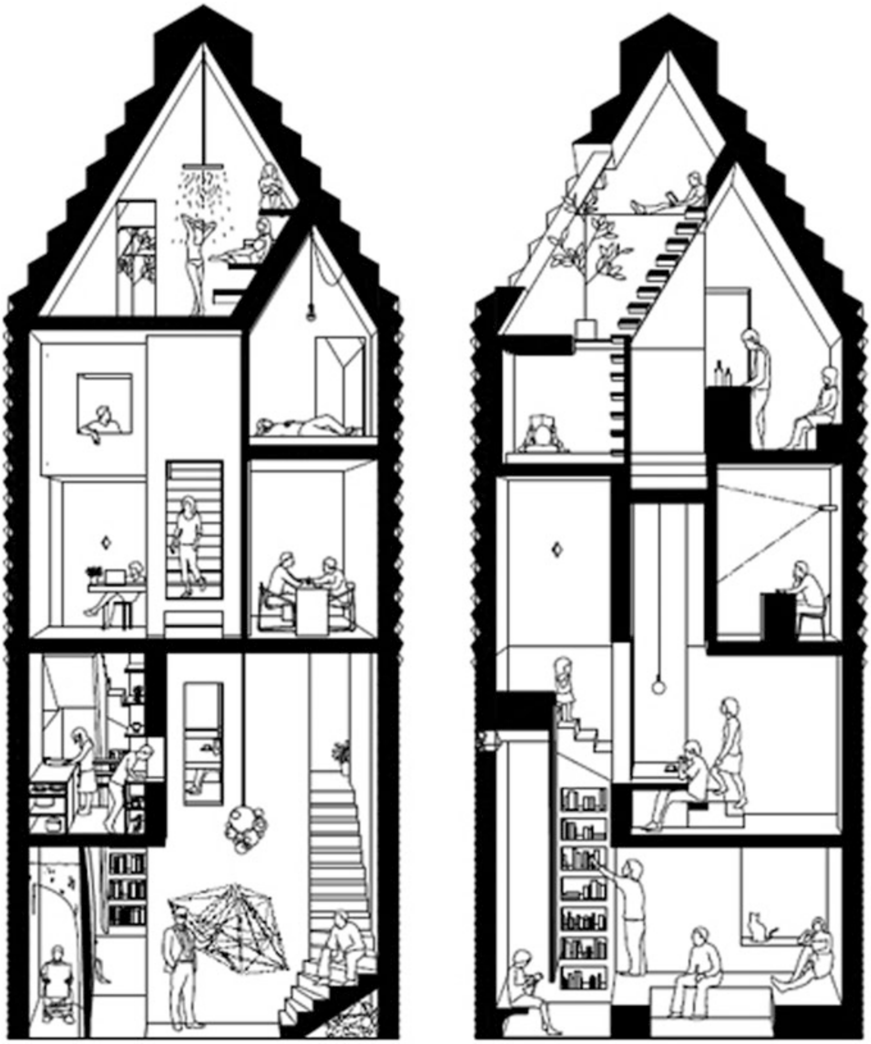


Fig. 9. Section of the project [41]

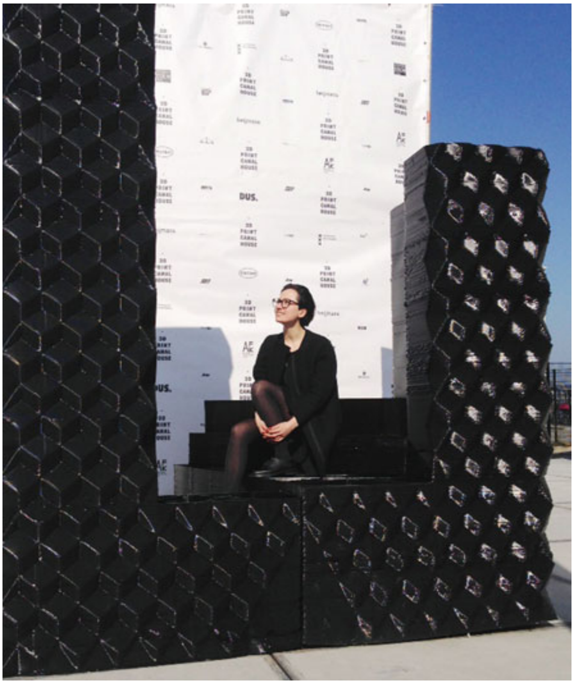


Fig. 10. 3D printed building block [42]

As we learn from the interdisciplinary research team, this initiative developed according to those “research & do” themes:

- KamerMaker: large scale 3D printing
- Sustainable 3D print material for the building industries
- New construction and building techniques
- Downloadable tailor-made architecture
- Smart building
- Scripted city planning [43]

The project is still under construction and planned to be completed in 2017.

4 Conclusions and Future Remarks

3D printing, an automated layer-by-layer production process, is a disruptive technology that can be used in construction industry to achieve economic and environmental benefits. The results obtained from this paper, in particular the analysis of case studies, presents that the potential of 3D printing technology is important for architecture.

These technologies have a potential to shape the future of construction industry. It is possible to claim that if it continues to be developed with a certain speed, it may revolutionize the construction process.

Although still in its infant days, current implementations of 3D printing for the construction industry could offer the following benefits [44]:

- from file to construction/direct printing on-site or in factories,
- using as much material as needed to manufacture the design so produce less waste,
- a variety of raw materials including recycled plastic, bioplastics, concrete and so on,
- precision,
- capable to adopt different types construction methods,
- capable of extruding multiple materials,
- reduced transportation and labor costs,
- to built complex shapes not possible with conventional construction,
- reduced health and safety risks on-site.

On the other hand, current challenges in the construction industry to be overcome can be listed as:

- it is still limited and an expensive technology,
- the industry is not familiar with this technology,
- 3D printers for construction such as concrete construction can be large and transportation to site could be costly.

The initial information indicates that 3D construction process has a potential from the sustainability point of view. Yet, it is necessary to have more practice and experience. Much further research has to be done on still unclear points like structural and mechanical stability, material life, toxic effect of materials etc. Especially, as the use of 3D printing in the construction industry is still in its infancy, the life cycle performance of the printed buildings/building components are still unclear. It is possible to claim that by focusing on these challenges, 3D printing can reach its maximum potential in the construction industry in the near future.

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