

Best Practices and Applications of 3D Printing in the Construction Industry

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Abstract

The construction industry is constantly looking for new ways to improve project efficiency and profitability. Many new technologies such as Business Information Modeling (BIM) programs, and project management software have been introduced to aid in preconstruction and on site coordination. However, traditional building methods have remained relatively unchanged for decades. 3D printing (3DP) is a promising new technology that has the potential to not only be an effective means of increasing project efficiency and profitability in the field, but also have positive environmental impacts. However, as it exists today, this technology is highly limited by size, material, skilled labor, and industry reluctance. This paper analyzes progressive 3DP companies that have been able to effectively employ this technology on a large scale. The purpose of this paper is to examine the current uses 3DP in construction and create an outline for the best practices and applications given the technology's existing limitations.

Key Words: 3D Printing, Best Practices, Limitations

Introduction

Three Dimensional Printing (3DP) refers to an automated additive manufacturing process in which three dimensional objects are created by laying down successive layers of material. The process starts with the creation of a 3D model using Computer Aided Design (CAD) software. The model is then sent to the 3D printer as a Stereolithography Language (STL) file. From there, the model is broken down into layers that can be successively applied on top of each other to form the object (Chen and Yossef, 2015). This technology has been utilized for a wide array of applications. For example, the medical industry uses 3DP technology to produce high quality bone and joint transplants, as well as anatomical models for research and analysis purposes (Murray et al., 2015). Architects use 3DP to create complex 3D models for their clients, 3DP is even used in the aerospace industry to print airfoils (Thomas et al., 1996). In recent years, 3DP technology has gotten a lot of attention from the construction industry as a promising building method. However, the current state of 3DP technology possesses many limiting factors that effect its integration into the construction industry.

History of 3DP

In 1981 Dr. Hideo Kadoma of the Nagoya Municipal Industrial Research Institute developed a system of printing solid layers of quick-drying photopolymers that corresponded with a cross-sectional slice of a CAD model, he called it Rapid Prototyping (RP). Three years later, Charles Hull patented Stereolithography which is a technique that utilizes the reaction between a liquid photopolymer and a UV laser beam. When exposed to the UV light, the liquid photopolymer will instantly turn each layer into a solid plastic mold consistent with the shape specified by the 3D CAD model. In 1992, Hull's company, 3D Systems, produced the SLA-1 which was the worlds first commercial Sereolithography Apparatus (SLA). That same year, Carl Deckard patented the Selective Laser Sintering machine (SLS) which is a similar technology that utilizes a powder photopolymer reaction rather than liquid (Goldberg, 2014). Throughout the 90's and into the early 2000's, SLA and SLS was used primarily in the industrial

manufacturing setting for casting small parts and components for a variety of plastic products. In 2005, ASTM recognized Additive Manufacturing (AM) as the standard term for all of these processes. ASTM defines additive manufacturing as “a process of joining materials to make objects from 3D model data, usually layer upon layer” (ASTM Standard, 2012.). 3DP is based on the AM methods.

Process	Description
Stereolithography (SLA)	Liquid photopolymer resin is held in a tank. A flat bed is immersed to a depth equivalent to one layer. Lasers are used to activate the resin and cause it to solidify. The bed is lowered and the next layer is built.
Selective Laser Sintering (SLS)	Utilises a laser to partially melt successive layers of powder. One layer of powder is deposited over the bed area and the laser targets the areas that are required to be solid in the final component.
3D Printing (3DP)	Based on inkjet printer technology. The inkjet selectively deposits a liquid binder onto a bed of powder. The binder effectively 'glues' the powder together.

Figure 1 – Summary of AM Processes
Source: (Buswell et al., 2007)

Current Uses of 3DP in Construction

Although 3DP is new to construction, the technology is being utilized in many ways by contractors and architects across the world. One of the major uses of 3DP in the construction industry is for creating scale mockups for building components. In an interview with Justin Porter, a Project Manager from Truebeck Construction, I learned that they have been utilizing 3D printers to create scale mockups for their project. These mockups are all created in house by their Virtual Design and Construction team which not only helps facilitate quick and easy communication between the contractor, architect, and owner, but also saves them time and money by eliminating long lead time from third-party mockups.

Other areas in which 3DP is being utilized on a larger scale is for the prefabrication of full scale building components such as interior walls and partitions. Branch Technology, a Tennessee based company, is a leading innovator in the field of 3DP using their patented “Cellular Fabrication” (C-Fab) method to prefabricate interior walls and partitions. This AM method involves 12’6” robot arm that moves along a 33’ long track capable of producing complex and exotic components with a building volume of 25’ wide by 58’ long. They have created an algorithm that generates a strong, yet lightweight geometric matrix made of ABS plastic and carbon fiber. This plastic matrix is reported to be three times as strong as traditional wood stud framing and can subsequently be insulated and finished with drywall as shown in Figure 2a (Simon, 2015).

Another leader in the world of 3D printing for construction components is a French company called XtreeE. They specialize in concrete printing and have utilized the technology to print 7’ x 7’ x 8’ storm water drains that are prefabricated in a warehouse and then dropped in place on site. These drains are printed and finished in only 9 hours (xtreee.eu, 2017)

Other companies, such as World Advanced Savings Project (WASP), are taking a more eco-friendly, and philanthropic approach. This Italian company has been experimenting with mixtures consisting of locally sourced clay, straw, lime, and sand to produce simple cylindrical shelters. Their goal is to provide inexpensive and environmentally friendly housing for low-income developing nations. These shelters could also serve as emergency shelters for areas affected by natural disaster (wasproject.it, 2017).



(a) C-Fab Wall Partitions

(b) 3D concrete printed storm drain

(B) WASP 3D Shelter

Figure 2 – Prefabricated Building Components

Methodology

The primary methodology I used in this paper was qualitative research taken from two large scale projects that employed 3D printing as their main means of construction. I also conducted quantitative research through an interview with a project manager from Truebeck Construction in order to gain insight to the thoughts and opinions of the use of 3DP in the industry today. My analysis includes a detailed case study of the two projects, identification of the advantages and limitations of the technology, and an evaluation of the best practices for the use of 3DP in construction today.

The objectives of this case study are as follows:

- To describe the various 3DP means and methods used for each project
- To highlight the time, cost, and materials savings associated with using 3DP
- To highlight the limitations associated with using 3DP
- To provide an analysis of the best practices and applications of 3DP in construction

Case Study

Winsun: 3D Printed House (2013) – 3D Printed Office (2016)

In 2013 a Shanghai based company called Winsun produced 10 small full-size prefabricated homes in just one day. Each home measured 215 square feet, and cost \$4,800 to build. The printer used to fabricate the walls stands 20 feet tall and 40 feet wide and moves along a 120-foot long track. The material that is extruded from the printer's nozzle is a trademarked mixture consisting of concrete, cement, glass fiber reinforced gypsum, and fiber reinforced plastics bonded together with a proprietary additive that enables the concrete to fully cure within a couple of days (depending on compressive strength). 50% of this material is sourced from recycled construction waste (Millsaps, 2016). The key to this mixture is finding a balance between flow-ability and build-ability so that the concrete can support itself without the need for formwork, while also maintaining a sufficient compressive strength. Although Winsun does not release their specific design, an optimal mix design for such a material has a fine aggregate to cement ratio of 1.28, a fine aggregate to sand ratio of 2, and a water to cement ratio of .48 (Hachem et al., 16). This

mix design is capable of reaching compressive strengths of up to 8,000 psi which is well above the International Building Code's 2,500 psi minimum strength for structural concrete (IBC Concrete Manual, 2017).

It must be noted that these homes are not entirely printed on site, but rather prefabricated in a factory and shipped on site where the walls are placed onto pre poured slab foundations and reinforced with traditional steel reinforcement. Additionally, the roof, doors, and windows are not printed using 3DP technology. Each wall is printed in a hollow fashion with an internal diagonal zig-zagging reinforcement system (see Figure 3a). This allows for the architects to implement calculated paths for insulation, plumbing, and electrical within their computer aided designs (Alter, 2016) treehuger.

Three years later, Winsun used the same printer and material to produce the worlds' first 3DP office building for the United Arab Emirates National Committee as their headquarters for the Dubai Future Foundation (DFF). This 2,700 square foot building was also printed offsite in a factory, cut in half for shipping purposes, and assembled onsite. The entire crew consisted of 18 laborers, including one printer operator, seven laborers for assembly, and ten laborers for mechanical and electrical (Alter, 2016). The total project duration from beginning of printing to finished assembly took only 17 days for a total of \$140,000 in construction and labor costs (Dalton, 2016).

Time, Cost, and Materials Savings

- 1.) Time Savings: Winsun's 3DP technique for the construction of both the 10 houses and office building in Dubai were reported to have, on average, a 30% schedule reduction than that of similar buildings using traditional construction methods (futureofconstruction.org, 2016).
- 2.) Cost Savings: Compared to traditional on-site construction methods, Winsun was able to save about 80% on construction and labor costs (futureofconstruction.org, 2016).
- 3.) Materials Savings: The accuracy and precision of Winsun's 3D concrete printer results in 30-60% less material waste as compared to traditional concrete placing (depending on size of printed components). This reduction in waste accounts for absence of formwork since Winsun's fast-curing concrete mixture is able to support itself while being extruded layer upon layer. Additionally, 50% of the concrete material used has been sourced from construction waste (futureofconstruction.org, 2016).



(a) Internal Reinforcement



(b) 3DP House



(a) 3DP Office

Figure 3 – 3DP Components and Final Products

Advantages of 3DP

3DP technology offers many advantages to the construction industry. The four main areas where 3DP can have the most significant effects are in labor efficiency, time and cost savings, environmental/economic impacts, and design complexity.

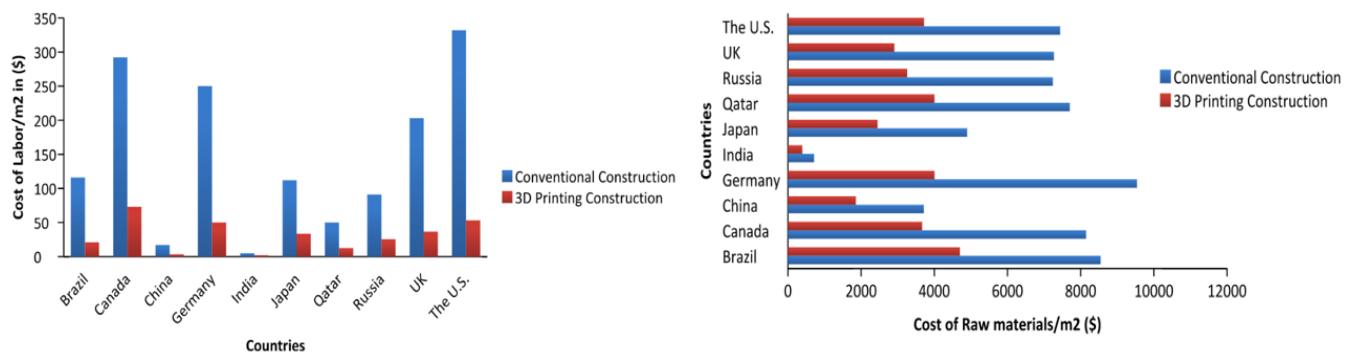
- 1.) **Labor Efficiency:** In recent years the construction industry has experienced a high demand for construction projects across all sectors of the industry. This upturn in work has resulted in an increased demand for skilled and unskilled labor. According to a 2017 Workforce Survey conducted by the Associated General Contractors of America, 70% of construction firms are having a hard time filling hourly craft positions. 51% of those firms also claim that they are having a hard time filling concrete worker positions (AGC, 2017). Concrete 3DP has the potential to effectively combat this shortage. As shown in the above case study, the fabrication of all concrete walls for an entire 2,700 square foot office building was completely automated, with the assistance of one printer operator. This demonstrates how 3DP can eliminate the need for large crews to produce components such as concrete walls.

- 2.) **Time and Cost Savings:** 3DP has the potential to produce significant reductions in on-site construction schedules, and large savings in construction hard costs. With 3DP prefabricated structural components, such as walls, floor panels, and roofing systems, a crew of 18 laborers were able to assemble a fully functioning office building in less than three weeks. Cost of material and labor alone can be reduced up to 80% using 3DP techniques (futureofconstruction.org, 2016). Figure 4, taken from a 2016 International Construction Cost Survey, shows the average cost savings of labor and raw materials using conventional construction methods compared to 3DP.

- 3.) **Environmental/Economical Impacts:** Many 3DP companies, like Winsun and WASP, are using inexpensive and sustainable materials that utilize construction waste and/or locally sourced clay and straw. This not only appeals to sustainable design but also to developing nations as a method for producing affordable housing. Additionally, by saving between 30-60% on raw materials used, 3DP also has appeal to advanced nations where labor costs and environmental standards are high.

- 4.) **Design Complexity:** 3D printers are able to move along a tri-axial plane (x,y and z direction) allowing them to be programmed to create irregular and exotic contours that are difficult and expensive to achieve using traditional forms or molds. This allows architects to design complex components without additional cost.

Figure 4 – Material and Cost Savings
Source: 2016 International Construction Cost Survey



Limitations of 3DP

Although the potential advantages of 3DP seem promising, the existing state of the technology possesses many limiting factors that impair its growth in the construction industry.

- 1.) The first and most obvious limitation is the sheer size of the printers. The largest printer in existence is Winsun's 20' tall, by 40' wide, by 120' long concrete printer which may seem significant but is only capable of producing building components rather than full systems. This hinders the technology's ability to create a truly 3D printed building because there will always be the need for traditional built foundations, reinforcement, and MEPF retrofitting.
- 2.) Material is next largest limiting factor. As it exists today, construction grade 3DP technology is only compatible with various concrete mixtures, and plastics. Such concrete mixtures range from lightweight air-entrained concrete, to eco-friendly concrete mixtures that utilize construction waste, to structural concrete. Plastics are typically used in construction for modeling and mockup purposes with the exception of Branch Technology's carbon fiber ABS plastic core wall components. While these materials are effective for the prefabrication of certain building components, they will never be able to replace traditional building methods like wood or steel frame construction. It is also important to note that 3D printers are only capable of printing one material at a time. This means that there are long turnover times associated with reprogramming, cleanout, and reinsertion of a new material before a new design can be printed.
- 3.) There is also high reluctance from general contracting companies to invest in 3DP technology. Although time and cost savings could be obtained in the future, there is a high upfront cost associated with purchasing the equipment. General contractors must also consider the time and cost associated with management and operation of the 3D printers. This involves an entirely new set of skilled labor and supervision.
- 4.) Building codes and regulations also pose as a large barrier for 3D printing in construction. Most building codes and procurement standards make no mention of 3DP technology therefore making it difficult to legally implement 3DP components onto large scale projects.

Best Practice and Conclusions

Given the existing advantages and limitations of 3DP within the construction industry, there are two main practices where the technology can be most effectively applied today. The first is in the prefabrication of uniform concrete and plastic wall components. Because the technology is so new, general contractors should not invest in the equipment themselves, but rather use experienced specialty subcontractors such as Winsun, or Branch Technology to perform the prefabrication. It can be seen from the above case study that the use of prefabricated concrete printed walls is an effective and inexpensive means of quickly assembling a building's superstructure. However, it is important for contractors to consider the size limitations when using 3DP on a project. The most ideal situation to employ 3DP concrete walls would be on a project no more than two stories high, with a uniform wall layout. Uniformity of the design is crucial in order to avoid long turnover times associated with the use of new material and reprogramming the printer with different CAD files. 3DP plastic walls are another viable application that can save time, money, and labor on a project. Specifically, for interior partitions that have particularly exotic designs, eliminating the need for complicated and costly formwork or molding.

The second most realistic application for 3DP is for use by general contractors to produce in-house scale mockups for building components. According to my interview with Justin Porter, a project manager from Truebeck Construction, in-house 3DP was used on his project to print a full scale mockup of a complex handrail system. Because of the complexity of the handrail, it did not meet the general building code, however the project team was able to use the mockup to prove that it was structurally sufficient to the city. Using 3DP for in-house mockups helps general contractors save time and money by not having to rely on a third party for their mockups, streamlines submittal processes, and enhances the communication between owner, architect and contractor.

The full potential of 3DP technology in the construction industry is yet to be seen, however if properly utilized for prefabricated wall components and in-house mockups, construction companies can start saving time and money on their projects today.

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