White paper: 3D printing construction
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When three-dimensional (3D) printing, as we know it, was first introduced to the general public, the concept was impressive and exciting. The sky was the limit when imagining objects made of plastic that could be printed at home. This innovation revealed disruptions on social issues such as gun control and organ transplants. Could it be possible to print a new liver or create a gun that would pass through airport security? These seminal discussions have raised the question about 3D printing innovation. How do we best channel it for social good? Specifically, the following white paper looks at the history, social impact, and production considerations available to date in order to inform future undertakings of 3D printed homes in response to veteran homelessness.

History

When Bill Gates was introducing the PC to the public in 1984, American entrepreneur Bill Masters filed a patent for his Computer Automated Manufacturing Process and System (US 4665492).[1] This filing is on record at the USPTO as the first 3D printing patent in history; it was the first of three patents belonging to Masters that laid the foundation for the 3D printing systems used today. His patent ended in 2009, opening the technology up for public use.

3D printing, also known as additive manufacturing (AM)[2], "involves technology that fuses material in order to build up a part, one layer at a time." While there is some semantics dispute, 3D printing *essentially* is a form of AM. However, AM is still in its infancy. The cost continues to radically reduce and the ability to create larger structures will continue to develop.

However, as 3D printing has become available to the masses, most hobbyists use what is now referred to as fused deposition modeling (FDM), sometimes also called filament freeform fabrication (FFF). This is the technology most common in the small printers purchased by everyday consumers ranging in costs from $250 to $1,000. FDM is a special application of plastic extrusion, developed in 1988 by S. Scott Crump and commercialized by his company Stratasys, which marketed its first FDM machine in 1992.[3] Today, when researching 3D printing for the consumer, Stratasys dominates the market.

Technology

3D printing is most often used for prototyping and rapid manufacturing. The 3D printer liquefier is one of the most critical components to this technology. One of the best descriptions of this process was written by US Vets Design, a 3D printing business for auto-parts company, founded by Justin Denton. Justin Denton's summary of the FDM manufacturing process explains how extruders for these printers

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[1] https://en.wikipedia.org/wiki/William_(Bill)_Masters#:~:text=Masters%20filed%20a%20patent%20for,3D%20printing%20systems%20used%20today.
[2] https://www.additivemanufacturing.media/articles/what-is-additive-manufacturing
[3] The technology used by most 3D printers to date—especially hobbyist and consumer-oriented models—is fused deposition modeling (FDM), a special application of plastic extrusion, developed in 1988 by S. Scott Crump and commercialized by his company Stratasys, which marketed its first FDM machine in 1992

have a cold end and a hot end. The cold end pulls material from the spool, using gear- or roller-based torque to the material and controlling the feed rate by means of a stepper motor. The cold end pushes feedstock into the hot end. The hot end consists of a heating chamber and a nozzle. The heating chamber hosts the liquefier, which melts the feedstock to transform it into a thin liquid. It allows the molten material to exit from the small nozzle to form a thin, sticky bead of plastic or other material that will adhere to the substance it is laid on. Different types of nozzles and heating methods are used depending upon the material to be printed. In the case of construction, the nozzle is larger and the most common material is cement or concrete.

Construction capability

Concrete homes are not a new concept. Some hot-climate countries still have an abundance of concrete homes. Prior to the development of stick-framed houses, concrete homes were not uncommon in the U.S. Wood-framed housing became known as less-expensive in the 20th century and replaced concrete construction across the country. If 3D printing of concrete homes were to prove to be significantly less expensive, this movement could revert a significant portion of construction back to the days of concrete homes across the U.S. In fact, one outcome might be the increase prices of concrete in the future.

As of now, companies range in what they claim they can print as part of the housing construction process. For example, 3D printing construction company, ICON, (winner of the South by Southwest Award for introducing the first permitted 3D printed home in the US.) claims its printer can complete the foundation, framing, insulation and exterior envelope leaving the finish work and utility systems/MEP to be installed after printing is complete. However, printing ability varies per company. *Some* of today's most competitive companies cannot print the foundation or insulation and still require structural support from traditional building methods because they have yet to be able to print load-bearing walls. As of now, no company known during this research period have reported being able to print a structural roof.

Companies report being able to build houses ranging from 2,000 to 4,000 sf. Permitted homes have typically been smaller in scale, to date. The 3D printing machine is limited in width, but can often do length of the home for as long as needed, thereby resulting in a more rectangular design. This also means that housing developed in rows are the most efficient for the printer because the printer can simply be moved down the line and continue to print as seen in the rendering here or here.

The ability to print multi-story homes also vacillates company by company. Some companies, like PERI Group, have had success in printing components of a multi-story house with at least two stories, with technology starting to reach towards three stories.

Ability to print on-site also varies per construction company. Some set up the printer on-site, whereas others, like Mighty Building, conduct the 3D printing in a warehouse like a pre-fabricated unit to offer modular options for those seeking smaller units such as a guest house on their existing property.

Cost per square foot (sf) also ranges significantly due to the variety of printing abilities each company offers. Some prices do not seem to offer significant cost benefit *yet*. Other companies offer the ability to complete the AM components of a 400-sf home for $8,000 or a 2,000-sf home for $40,000 (~ $20/sf).

With the latter example, other additives might include the cost of the initial permits due to the novelty of this technology, the costs of special materials (such as water) to operate the printer, or the cost of incorporating a hybrid approach to the build out. This needs to be explored with each company based on past examples of homes *actually* built. Additionally, consider the final price after subsidizing what the technology could not create with what is typically produced by traditional building methods (See *Conclusion*). Cost remains the biggest unknown factor. According to the National Association of Home Builders, the average cost of a home across America is approximately $114/sf.[4]

Benefits and risks

Some of the benefits of utilizing 3D printing/AM for construction purposes are exceptional.

- AM allows for customizing a portion of the design at the last minute.
- The 3D printed components of the home can be installed and operated by two to four people.
- The technology can produce very complex shapes or geometries that would be otherwise impossible to construct by hand. This includes hollow parts, such as honeycomb, or parts with internal truss structures to reduce weight.[5]
- The speed in which the AM components of a home can be printed vastly outperforms traditional build timelines. The AM components can be printed in a single day compared to weeks or months of building time required with stick-framed homes.
- Additionally, once a roof is able to be printed, the majority of the house could be fireproof. This is exceptionally valuable in areas prone to wildfires like California, Colorado and Washington, among other countries outside of the U.S.

However, there are still risks involved with AM/3D printing for construction purposes.

- As of now, there is significant misinformation being deployed in the United States about 3D printing for construction. It appears to be a race among developers and technicians to be the "first" or the market leader. As a result, some companies are reporting achievements that are still in theory and have yet to be actualized or built. There are also several companies claiming to be the "first 3D printed/permitted home." One company, Sq4D, seems to be marketing itself as if it is mass producing 3D homes whereas it is mostly marketing renderings for future development. When receiving an article or an image, be curious as to whether this building was actually constructed or if the viewer is simply looking at a rendering of a hopeful development.
- This technology remains limited in terms of the commercially available materials that can be processed with AM and the size of the parts that can be made by AM machines in the market.[6]
- For most of the existing designs, the mechanical, electrical, and plumbing (MEP) connections have to have exterior hookups. Designs that allow hookups interior to the house are just now being tested and implemented by select companies.

[4] https://www.newhomesource.com/learn/cost-to-build-house-per-square-foot/
[5] https://immersiveeducation.org/printing
[6] https://www.additivemanufacturing.media/articles/beginning-your-am-journey-picking-your-pathfinder

Social and environmental impact

As mentioned, 3D printing also has been used in the humanitarian and development sector to produce a range of medical items, prosthetics, spares and repairs. In terms of construction, the social impact possibilities are significant. The issue of housing affordability is prevalent across the U.S. Home building has not kept up with demand and population growth. This has contributed to a growing housing crisis. Traditional home building methods have inefficiencies and produce notable waste. These critical problems continue to drive up costs creating increasing issues with affordability for the average person. 3D printed construction offer the hope of a more affordable home due to the decrease in material waste, decreased demand for labor, streamlined efficiencies, and reduced transportation costs.

In terms of environmental impact, there seems to be some clear benefits. As opposed to traditional manufacturing in which pieces are cut from larger blocks of material, AM creates products layer-by-layer and prints only relevant parts, wasting much less material. Additionally, this wastes less energy in producing the raw materials. By making only the bare structural necessities of products, AM products are lighter, thereby reducing the energy consumption and greenhouse gas emissions caused by transportation. Additionally, as concrete homes become more popular, timber would no longer be sought as readily, thereby reducing the depletion of natural resources.

Some have expressed potential disadvantages to the environment. Despite AM reducing waste from the subtractive manufacturing process by up to 90%, the AM process creates other forms of waste such as non-recyclable material (metal) powder.[7] Additionally, the machine uses a lot of water. Some printers use up to two gallons of water per minute.

Conclusion

As of today, this technology for construction purposes is still thoroughly in development. To date, some homes have been 3D printed and permitted in the U.S. Globally, built work range from single- to multi-story, with varying degrees of utility placement, size, costs, and scope completed by AM printing versus a hybrid of printing and traditional methods of construction. Because the printing ability varies by company to a highly significant degree, it will be critical to collect multiple proposals during the RFP stage. Specifically, look to understand each company's 1) technological ability and 2) actual experience with built work versus conceptualized modeling.

Costs will need to consider not just the base price per square foot, but the cost to run the technology including space and water use, costs of remaining components of the build out, permitting costs of this new method of construction and the ideal land space.

If the price, waste, time and technology can be produced to achieve economies at scale, this technology has real potential to not just redefine the construction industry, but to flip the way in which we respond to the housing crisis in America. It will continue to be a great learning opportunity in response to homeless veteran housing in Arizona, per the Milanovich Trust interests.

[7] https://commons.erau.edu/cgi/viewcontent.cgi?article=2469&context=publication