Industrial Revolution

Every home that is built is a representation of compromises made between different and often competing goals: comfort, convenience, durability, energy consumption, maintenance, construction costs, appearance, strength, community acceptance, and resale value. Consumers and developers tend to make tradeoffs among these goals with incomplete information which increases risks and slows the process of innovation in the housing industry. The slowing of innovation, in turn, negatively affects productivity, quality, performance, and value. This department piece features a few promising improvements to the U.S. housing stock, illustrating how advancements in housing technologies can play a vital role in transforming the industry in important ways.

3D Concrete Printed Construction: Building the Future of Housing, Layer-by-Layer

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Abstract

Three-Dimensional Concrete Printing (3DCP) is expected to address many challenges facing concrete construction today and offer new design possibilities. 3DCP is an automated construction process that builds structures layer-by-layer from 3D modeling data. With the looming housing crisis, the construction industry needs to rethink how to build safe, affordable, and sustainable homes. 3DCP technology offers potential innovative solutions to increasing the supply to homes across the nation.

The Status Quo

The typical American home built partially or fully with concrete is constructed using formwork, a technique that supports a wet concrete mixture as it cures in place. The formwork process uses temporary molds or structures fabricated with wood or steel to cast, curate, and harden concrete (see exhibit 1). The impermanent nature of conventional wooden formwork approaches means that eventually discarded materials are destined for landfills, constituting a major source of waste in the construction industry. Steel framework is also bulky and burdensome to store, transport, and erect.

Exhibit 1

Wood Formwork Used to Pour and Harden Wet Concrete

Typical formwork construction made with wood, used in the casting and hardening of structural building components from wet concrete mixtures used in traditional concrete construction practices.

Source: https://engineer-educators.com/lessons/formwork-2/

The installation and deconstruction of formwork are labor-intensive and time-consuming, amounting to roughly one-half the total cost of traditional concrete construction (Llatas, 2011). There are worker safety concerns related to traditional concrete formwork approaches, and the labor involved in the erection of molds and the placement of steel reinforcement is physically demanding.

3D Concrete Printed Homes

Emerging innovations in automated construction and additive manufacturing practices could significantly change how buildings are delivered. The idea is not entirely new: in 1917, Thomas Edison invented a device that would build a concrete house in a single pour (Edison, 1917). A century later, the advent of technological advances in concrete printing has become a reality. The introduction of Three-Dimensional Concrete Printing (3DCP) technology reveals new opportunities for innovation in the building industry. 3DCP, also referred to as additive manufacturing, might lead the United States to be able to build homes quicker, safer, and more sustainably. 3DCP involves an automated construction process that builds structures layer-by-layer from 3D modeling data. The 3DCP technology consists of a robotic arm connected to a nozzle from which the concrete flows and is poured in successive layers (see exhibits 2, 3, and 4).

Exhibit 2

Robotic Arm Over the Frame of a Home

Partially constructed wall showing layers of concrete built with 3D concrete printer; robotic gantry-arm system is shown in the background and above the wall structure.

Source: Zachary Mannheimer, Alquist 3D

Exhibit 3

The Outer Frame of the Home with Spaces for Doors and Windows

Layered walls that make up the outer frame of a home being built with 3D concrete printing construction.

Source: Zachary Mannheimer, Alquist 3D

Exhibit 4

Close-up of Double Wall Construction

Top view of newly printed wall with metal frame for robotic gantry-arm in the background.

Source: Zachary Mannheimer, Alquist 3D

With this technology, the concrete is formulated to optimize some combination of workability, setting, hardening time, and mechanical properties for the specific requirements of the building. There are two major techniques in 3DCP: (1) extrusion-based and (2) powder-bed-based. Both 3DCP techniques use material formulations which differ compositionally from traditional concrete by adding three new ingredients: (1) a reinforcing material; (2) an adhesive; and (3) a hydrator (Allouzi, Al-Azhari, and Allouzi, 2020). This formulation gives 3D concrete special attributes, including the ability to maintain its shape when wet, eliminating the need for formwork and reducing waste.

Extrusion-Based 3DCP

Modern 3DCP began more than two decades ago with Dr. Behrokh Khoshnevis' Fused Deposition Modeling (FDM) method, partially funded through a collaboration between the U.S. Department of Housing and Urban Development (HUD) and the National Science Foundation. FDM uses a computer-controlled machine to continuously extrude layers of a cementitious mixture (Khoshnevis, 2004). Today, Extrusion-Based 3D Concrete Printing is still using FDM techniques. Modern 3DCP instruments extrude wet mixtures from a nozzle mounted on a robotic arm, gantry, or crane to print structures layer-by-layer (see exhibit 5). Extrusion-Based 3DCP technologies and equipment are widely designed and used for on-site construction applications, such as large-scale building components with complex geometries.

Exhibit 5

Extrusion-Based 3D Concrete Printing

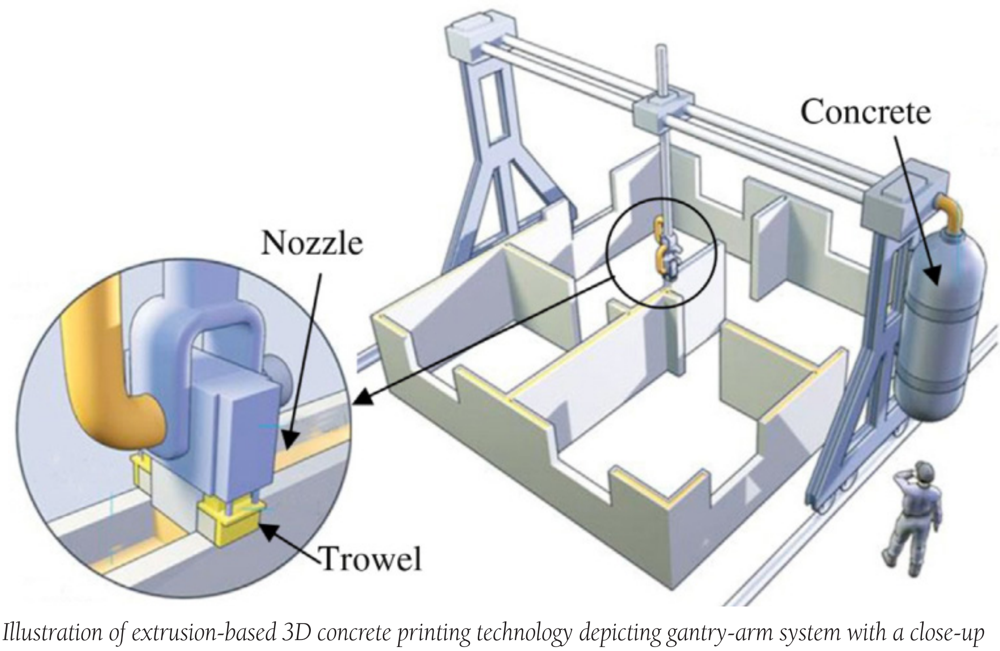

Illustration of extrusion-based 3D concrete printing technology depicting gantry-arm system with a close-up graphic of extrusion nozzle; includes a figure of a person as a portrayal of the scale and size of equipment.

Source: Sanjayan and Nematollahi, 2019

Enrico Dini developed the second major 3DCP technique (exhibit 6). It creates solid stone structures using sand and binding materials rather than traditional cement mixtures (Colla and Dini, 2013). This method involves 5mm segments of sand or other powder-based mixes that are continually and gradually injected with "ink" (binder liquid) in pre-programmed computer-specified locations, layer-by-layer. Once dry, whatever unbounded powder-based material remains is removed to be reprocessed, leaving only bounded materials and revealing the final desired structure. Powder-Bed-Based 3DCP techniques can create complex, creative, and interesting designs for buildings and structures. Off-site manufacturing processes predominately use it for precast components.

Exhibit 6

Example of Technology Used in 3D Powder-Bed Printing

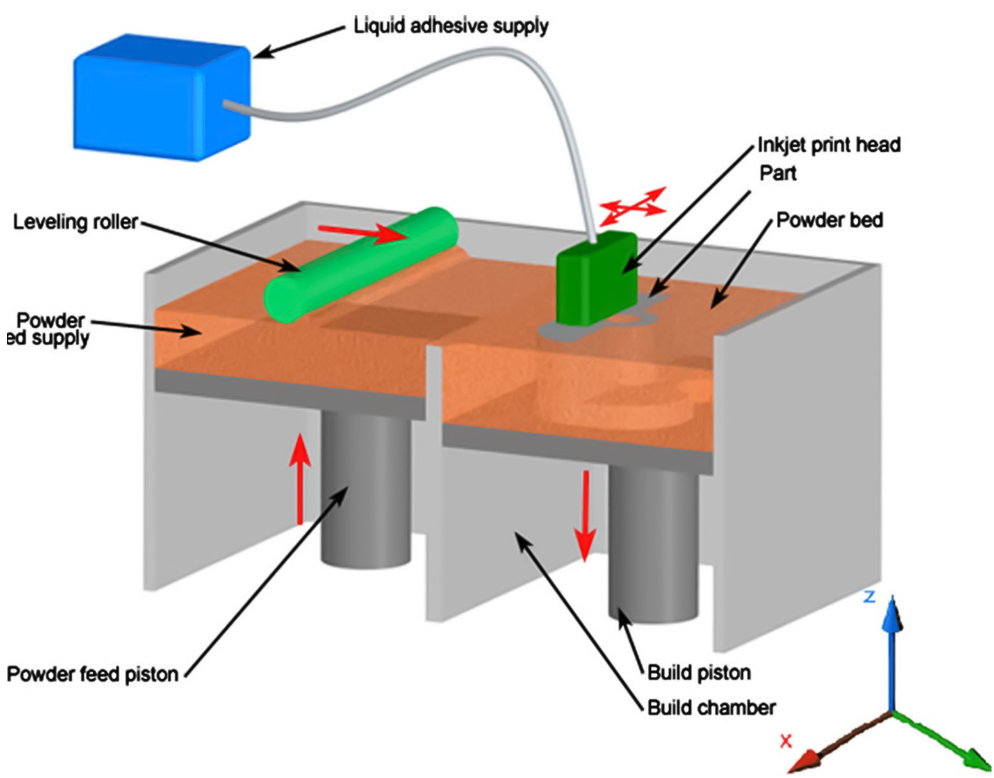

Illustration of powder-based 3D concrete printing technology depicting the process of chemically binding an adhesive liquid medium, or a binder, with a dry building material, the powder.

Source: Shakor et al., 2017

Current HUD Research and Industry Developments

As it exists today, construction-grade 3DCP technology is only compatible with a limited number of concrete formulations (Kidwell, 2017). Consequently, most current research studies are focused on developing new concrete material formulations for 3D printing to obtain the appropriate material performance properties and extrudability that enables the material to be printed continuously in layers. HUD funded two studies to understand the role of 3DCP and affordable housing. HUD expects the final reports for the following two studies in winter 2023.

"3D Printed Walls: Identifying Best Practices for Residential Building Product System Integration and Conducting Market Barriers Research" —Home Innovation Research Labs, Inc.

> Home Innovation Research Labs, Inc. will partner with Black Buffalo 3D Corporation, a leading 3D Concrete Printing company, and the American Concrete Institute's (ACI) subcommittee on 3DCP to evaluate wall system components, including windows and doors (for example, flashing/sealing details), wall penetration methods for installing utilities (such as water and electrical), and wall connections between the roof and foundation. In addition, Home Innovation Research Labs, Inc. will conduct qualitative research among home builders and contractors at the job site and through a national survey to understand the challenges and opportunities to accelerate the adoption of 3DCP.

"Cooperative Research to Enable 3D Printed Concrete Single-/Multi-Family Housing Technologies" —Texas A&M Engineering Experiment Station.

> The objectives of this project are to: (1) demonstrate, document, and validate a rational design procedure for 3D printed concrete residential construction, accounting for seismic loads; and (2) develop, in coordination with a stakeholder-based Peer Review Panel, a "Best Practices document" to serve as a U.S. code proposal that can be adopted by local jurisdictions and national-level provisions and design codes. This project will include large-scale testing of 3D printed concrete walls with and without integrated reinforced concrete elements, development of design capacity equations, and a comprehensive seismic collapse assessment study of a set of 3D printed archetype buildings to demonstrate their margin against seismic collapse.

The Future of 3DCP Housing

Due to the emerging and innovative nature of 3DCP, the technology must face and overcome some challenges. Because this technology is still being explored and adopted, some aspects remain proprietary, such as the mixture of concrete and the design of robotic nozzles. The aesthetics of cured structures will therefore vary with each company. Ongoing research is still informing improvements to concrete mixtures for appropriate pours, ensuring stability in homes. Furthering industry knowledge is crucial for creating prescriptive methodology and standardization, making 3DCP more readily available and less expensive.

Possible benefits of 3DCP over conventional concrete construction include the following:

- 3DCP lends itself to precise and predictable outcomes, which reduce overall construction costs and time by building continually from start to finish at rapid rates.
- Automating construction allows builders to reallocate their labor toward more skilled tasks, such as plumbing and electrical.

- 3DCP reduces the volume of waste and discarded materials, lowering total construction costs and increasing sustainability.
- 3DCP increases worker safety and reduces injury rates by eliminating dangerous tasks associated with conventional formwork construction, such as working from heights or physically demanding labor.

Currently, most building codes and procurement standards do not recognize 3DCP technology. This impediment makes it difficult to build on a large scale because projects must be reviewed and approved through alternative means to demonstrate compliance with local building codes. The lack of integration into the International Building Code and the International Residential Code is a barrier to the widespread adoption of 3DCP in construction.

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Additional Reading

AC509 - International Code Council (ICC) approved an Acceptance Criteria for 3D Automated Construction Technology for 3D Construction. https://icc-es.org/acceptance-criteria/ac509/.

Revisions Enhance ICC-ES AC509 to Include Multi-Story Building Construction. https://icc-es.org/news/revisions-enhance-icc-es-ac509-to-include-multi-story-building-construction/.

2021 International Residential Code—Appendix AW: 3D-Printed Building Construction. https://codes.iccsafe.org/content/IRC2021P2/appendix-aw-3d-printed-building-construction.

UL 3401: Outline of Investigation for 3D Printed Building Construction—covers the evaluation of building structures and assemblies such as panels, walls, partitions, floor-ceilings, roofs, columns, and beams fabricated using an additive manufacturing or 3D printing process. https://www.ul.com/news/build-trust-3d-manufactured-buildings-ul-3401.