Applications in architecture and construction

by Charles Overy

AM for architecture and construction is expanding with many projects moving from the conceptual and technology demonstration phases into early stage commercialization. AM techniques continue to be used to improve traditional architectural products. The use of AM for the built environment occurs in three different categories. At the largest scale, various innovative methods are used to construct entire buildings. Second, smaller AM machines are being used to fabricate structural parts. Increasingly, prototypes and experimental parts are being produced, and some are aimed at making end-use parts. Third, 3D printing has become well-accepted for producing scale models for visualization and design review. Both low-cost 3D printers and high-end industrial machines are used for this purpose.

The largest AM machines are designed to build complete or nearly complete buildings. Currently, the build volumes are limited to relatively small structures like petite offices and houses. The majority of the machines extrude low-slump concrete in a manner similar to polymer material extrusion systems, but on a much larger scale. A range of mechanisms have been used to control the position of the extruder including *xyz* gantry or delta systems. Some have tried to reduce the machine footprint. Instead of using a system that is larger than the proposed structure, the positioning device is located within the structure and reaches outward. Many systems use commercially available industrial robot arms as the positioning device. To construct entire buildings, the machine reach must be extended. This is done using machine tracks, rail systems, small pick-and-carry crane mechanisms, or a combination of devices. CyBe and Apis Cor, both commercial ventures that market robotic-based extrusion machines, are examples of this trend.

In many countries, a wide range of local building codes and regulations must be met before innovation in the construction industry can succeed. One advantage of low-slump concrete is that the material properties of many formulations are well understood from its conventional use in construction. However, new dispensing methods require a review of structural and durability characteristics, as well as the ability to add reinforcement, such as steel, to increase tensile strength. As with smaller extrusion machines, issues with layer-to-layer adhesion cause a reduction in strength in the *z* direction. With most buildings, the vertical axis is typically in compression, however, the anisotropic material properties are still a concern. Adoption on a wide scale will depend on new processes that meet building code testing and certifications.

Recognizing these limitations, system vendors and academic projects have demonstrated ways to print formwork for traditional concrete pours. Apis Cor demonstrated the use of concrete extrusion to print a foundation form that was backfilled with standard concrete. MIT demonstrated the additive manufacture of a building scale form using sprayed urethane foam. Both methods show promise for reducing the labor and geometric restrictions inherent in traditional concrete formwork. They also maintain a more traditional workflow and material specification.

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Technology demonstrations and startup ventures are more common where building codes are less strict or where local initiatives override lengthy building material certifications. For example, Dubai has a strategic initiative to 3D print 25% of all new buildings by 2025. The initial goal is to 3D print 2% of new buildings in 2019. Meeting these goals has created a market opportunity for several companies.

WinSun is a Chinese company that has previously demonstrated the offsite fabrication of several structures in China. It 3D printed and delivered a single story office building for the Dubai Future Foundation. The building was designed by the U.S. architectural firm Gensler. WinSun has had several other notable successes. It signed a deal to lease up to 100 printers to the Saudi Arabian construction firm Al Mobty for $1.5 billion. It has also announced a three-year strategic partnership with the U.S. Fortune 500 firm AECOM to pursue 3D printing opportunities worldwide.

Digital workflows from the designer to fabrication continue to produce exciting and innovative structures as well as new methods of building. Industrial robot arms are not limited to fabricating in strictly vertical layers. They are capable of extruding some materials in "bridging" patterns into open space. Using these techniques, Branch Technology has used a wire feed welder to build metal structures.

Robotic additive manufacturing at Branch Technology, courtesy of SHoP Architects

Extrusion devices are capable of fabricating open space structures, and architects are beginning to ask for these types of methods. This indicates a demand for actual services rather than just technology demonstration projects. Innovative architectural design firms such as SHoP Architects are now using 3D printing as an enabling technology for important projects.

"Flotsam and Jetsam" structure designed by SHoP Architects for Design Miami and printed by Branch Technologies and Oak Ridge National Laboratories, courtesy of SHoP Architects

Full-scale buildings made by AM attract attention and continue to challenge the boundaries of what is possible. However, 3D-printed buildings are at a very early stage and have not yet made a substantial economic impact on architecture and construction. Promising commercial AM applications in architecture and construction will come from the improvement of traditional techniques and product development workflows.

Some of the companies mentioned previously have recognized that the barriers to entry are lower for relatively small concrete objects with fewer regulatory hurdles. They are producing designer items such as benches but also experimenting with less visible parts that have potentially large markets. Examples include large concrete waste and stormwater connections. The fabrication of concrete forms has also matured quickly. FreeFab has developed a wax-based AM machine that has produced thousands of unique molds for the London Crossrail system. The system is a hybrid of near net shape 3D printing and machining, and dramatically cuts the time to produce a concrete mold.

Several innovative industries are now using AM routinely as part of their industrial design workflow. Example products include residential and commercial lighting, plumbing fixtures, and heating and air conditioning parts. The development of low-cost polymer extruders with large build volumes has enabled experimentation with relatively low financial risk.

The production of end-use products by AM will become increasingly feasible as more machines with larger build volumes, greater reliability, and lower costs come to market. The production of these products is currently limited because AM costs for larger objects cannot compete with traditional manufacturing. However, innovations in AM systems and materials may change this situation over time. New developments, such as HP's Multi Jet Fusion system, may provide cost-effective production of parts such as connectors and brackets. Instead of parts substitution, companies are using AM technologies to add value to existing products. Aectual is using robotic-based AM to add value to terrazzo flooring by making custom patterns and panels rapidly.

A robot printing elements of custom terrazzo flooring, courtesy of Aectual

AM technologies continue to have a significant impact on architectural design visualization. The use of AM in the production of scale models is now a mature industry. Strong global demand for architectural and construction services has provided many architectural offices and design–build contractors with sufficient capital to explore new technologies. As a result, companies that were previously outsourcing 3D printing as a design tool are now acquiring low-cost or mid-range machines. The global design firm HOK has adopted Ultimaker 3 machines in a move that resembles Ford Motor Company's adoption of low-cost, desktop 3D printing systems in 2012.

In architectural modeling, appearance matters much more than the mechanical properties. Although models are scaled representations, they still tend to be large, traditionally 0.5 x 1.0 m (19 x 39 inches). AM models used for visualization and iteration typically have a very short lifespan. Architects usually make only one final model, but if costs were lower, they would probably use AM technology more frequently to iterate designs.

Large model sizes and resulting high material costs have typically led architects to favor systems with large build volumes and lower operating costs. The widespread availability of polymer material extrusion systems means that more architectural models are being produced using this technology. However, material extrusion technology is not ideal for this application because of the need for support structures. Powder bed fusion systems are more compatible and binder jetting technology is particularly useful. Binder jetting systems have been used since 2000 by several companies, including Foster + Partners, Morphosis, and LGM.

Large interior model of building amenities made by LGM for DDG Architects, courtesy of LGM

Other technologies are being used for model making, particularly the PolyJet systems from Stratasys and ProJet material jetting systems from 3D Systems. A significant drawback to using material jetting systems for large models is the high cost of photopolymers.

The monochrome version of the HP Multi Jet Fusion system is not very suitable for architectural models. The gray base color, usually dyed black, is not suitable for most architectural visualizations. The multi-color HP machines announced in early 2018 could become very competitive with the ProJet CJP platform.

Material extrusion systems from Stratasys initially sold well into some sectors of the architectural market. The primary barriers to wider acceptance are long build times for large parts and aesthetics that are not suited to artistic forms. Professional model shop Zoyes East in Detroit used Stratasys' online AM service to rapidly produce many scale building models on a tight deadline. The availability of substantial production capacity using Internet tools is transformative.

Laser-based powder bed fusion and vat photopolymerization systems are attractive for architecture applications because of material durability and dimensional accuracy. However, machine cost puts these systems out of reach for all but a few large architectural firms. Large service providers are able to compete because of their technical expertise and efficient cost structure. Increasingly, architecture firms with in-house material extrusion machines are looking to vat photopolymerization for more elaborate and accurate parts.

Art museum model containing parts made by binder jetting,
vat photopolymerization, powder bed fusion,
and laser cutting, courtesy of LGM

The architecture and construction industry continues to experiment with low-cost desktop material extrusion machines and the small DLP-based vat photopolymer systems. These machines are useful for the less experienced to gain an understanding of how AM can meet the unique workflow challenges. When selecting a low-cost machine, it is important to understand that some method of support material for overhanging features is required. Low-cost but relatively robust dual-extruder machines, such as the Ultimaker 3, offer soluble supports that were previously only available from Stratasys.

To use AM machines successfully, it is important to develop skills in data preparation and other related competencies. Unsuccessful adoption of low-cost machines can result due to a lack of investment in the resources needed to develop new workflows. It can also be the result of inflated expectations of what a machine can deliver. A significant opportunity exists to serve the mid-range market with professional-grade machines in the $20,000 to $90,000 price range. However, material costs cannot exceed that of binder jetting systems, which are less expensive than for powder bed fusions systems.

The demand for full-color 3D printing is strong, but the cost and difficulty of achieving good results is limiting its application. Material extrusion machines that use different colors of filament do not provide the resolution necessary for most architecture and construction applications. The Stratasys J750 full-color material jetting system could be useful for architectural visualization. However, high prices and new data handling requirements for color models contribute to slow adoption for scale models. The entrance of both HP and Mimaki into the color 3D printer market will bring competition and innovation. Color binder jetting systems, such as the ProJet CJP machines from 3D Systems, remain the only widely used color AM technology for architectural visualization.

Color 3D-printed model of a hospital redevelopment proposal made by LGM for L.F. Driscoll, courtesy of LGM

Architectural models of very large and complex structures result in significant data challenges. Despite improvements in CAD systems, it is not yet possible to 3D print most scaled architectural models directly from CAD data. The industry standard workflow for architectural models is to export the data into a mesh format and then modify it using AM software tools. Software packages such as Magics, Netfabb, and Blender require high-quality triangular mesh data to successfully prepare a part for 3D printing.

Architectural data typically consists of hundreds (or in the case of Revit data, tens of thousands) of discrete objects or shells. Boolean operations with high shell counts and many coplanar or nearly coplanar surfaces rarely result in useable data. This problem has not been adequately addressed, but the influx of new customers means that the problem is attracting renewed attention. Most of the innovation is coming from new entries into the AM software field. Model modification and repair tools such as Magics from Materialise or Netfabb from Autodesk are still a necessity for any serious involvement in AM. However, new work on voxel-based solutions, as well as more robust Boolean and repair algorithms, means that other solutions may become available.

The outlook for increased adoption of 3D printing technologies by architecture and construction companies is promising. Long-term market opportunities exist for companies that can disrupt the current cost model for producing full-scale building components. Large-build-volume material extrusion machines and other innovative AM devices have good opportunities for market expansion. This will be driven by the growing demand for automation, customization, and faster prototyping in a wide range of architecture and construction applications. For visualization, the production of scale models is a proven market with a significant number of established providers.