# Design Potential for Large Scale Additive Fabrication: Freeform

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This paper focuses on recent developments in rapid prototyping and manufacturing industry and specifically in the field of architecture and construction. The paper mainly revisits the idea of a digital design environment for additive fabrication first raised by Buswell and De Kestelier (2009) and possible future developments within that field (Bernaerdt, Van Hauwaert and De Kestelier, 2009). This is then illustrated through the design and construction of an additive fabricated concrete wall component.

## FROM RAPID PROTOTYPING TO MANUFACTURING

Rapid prototyping is a fairly new fabrication technology. The first commercially available machines came on the market in the late eighties and early nineties. These first rapid prototyping machines were able to construct physical objects directly from a CAD model. This was done by solidifying a powder or liquid layer by layer. The process adds material incrementally and is therefore also called an additive fabrication process. Prototypes could be made fast and efficiently directly from 3D digital data. This technology was adopted rather quickly by mechanical engineers and industrial designers. The material characteristics of these rapid prototyped models were in the early days rather poor. They were often brittle and degraded over time. (Wohler, 2007)

A lot of research and development has been done in the last two decades on the improvement of the material properties of rapid prototyping technology. Early rapid prototyping machines were only able to produce parts in brittle resins and sintered nylons. It is only in the last decade that materials such as, ABS, carbon-reinforced polyamide, polycarbonate and even metals such as titanium and stainless steel can be used (Wohler, 2010). The material properties improved in such a degree that these physical prototypes often could be used as the actual products. This is where the shift from rapid prototyping to rapid manufacturing occurs. Rapid manufactured products are products that are directly fabricated through a layered additive fabrication process. The step from prototype to actual manufactured object is rather small once the material properties of additive fabrication technology improved.

There are currently a wide range of engineering fields where rapid manufacturing technology has been used: aerospace, automotive (F1), medical tooling, implants, dentistry, etc. These industries often use rapid manufacturing for small production series with a high geometrical complexity. In the last few years a growing number of consumer goods companies have also started to use rapid manufacturing to produce unique high end designer goods. Examples of these are Freedom of Creation and Materialise.MGX.

In architecture rapid prototyping is used to produce physical scale models. Architectural design practices such as Morphosis (Marty Dosher, 2004) and Foster+Partners (De Kestelier and Peters, 2008) have been the early adopters of this technology. It is only in the last few years that physical model making through rapid prototyping has become main stream. It was for example only in 2007 that Wohler Associates started to mention 'Architecture and GIS' as a separate industry in their yearly industry report on additive fabrication (Wohler, 2007).

## ADDITIVE MANUFACTURING IN ARCHITECTURE

Within the fields of engineering and industrial design, the shift from prototyping towards direct manufacturing was mainly driven by improvements in materials. The step from prototype to actual manufactured object is rather small once the material properties of additive fabrication technology improved. This shift is much more difficult when we try to build architecture instead of architectural models through additive fabrication.

Scale is one of the main differences between industrial design and architecture. Architects are used to work at scale. Drawings and models are always a scaled representation of the actual architectural design. The scale of architectural models can easily range between anything from 1/10 to 1/1000. There will need to be a massive scaling exercise to use additive fabrication as a construction technology for buildings or building components. This means that for architectural projects a rapid or additive manufacturing process volumetrically typically needs to be scaled up in the order of 10^3 to 10^9.

Since the mid nineties a few universities and companies have started to attempt to apply additive fabrication in architecture or construction (Gardner, 2009) Three processes are currently actively pursued: Contour Crafting (Koshnevis et al, 2006), D-Shape (Dini et al, 2006), and Freeform Construction (Buswell and De Kestelier, 2009).

Contour Crafting has been developed at the University of Southern California by Dr. Behrokh Khoshnevis. It is an additive fabrication technique that produces fixed width walls by robotically depositioning an internal and external trowelled skin. The cavity between these skins is then filled with a bulk material through that same robotic arm. (Koshnevis et al., 2006).

**Fig. 1:** The additive manufacturing machine capable of producing large (2m x 2m x 2m) parts out of concrete.

**Fig. 2:** The large computer controlled 3 axis steel gantry system deposits concrete with high precision.

**Fig. 3:** Wall section with cavities that can incorporate services and locally optimised insulation and reinforcement.

Enrici Dini has been developing a large scale fabrication technology that is similar to the 3D printing technology from Z-Corp. It deposits a thin layer of sand over the full bed size of the printer (4mX4m). This sand has been pre-mixed with a catalyst that chemically hardens when it comes in contact with an inorganic binder. This binder is jetted onto the sand through a series of jets. Just as with Z Corp.'s 3D printing technology, the sand is used as its own support structure.

The Freeform Construction project from Loughborough University will be used in this paper to exemplify the constraints and possibilities of large scale additive fabrication.

## Freeform Construction Project at Loughborough University

The Freeform Construction project was initiated by the Innovative Manufacturing and Construction Research Centre (IMCRC) at the Loughborough University and is funded by the UK Engineering and Physical Sciences Research Council (EPSRC). It also comprises of a range of industrial partners such as Foster+Partners and Buro Happold.

Over the last 4 years an additive manufacturing machine has been developed and is capable of producing large (2mx2mx2m) parts out of concrete (Fig.1 shown on next page) The process deposits concrete through a computer controlled. The process can be easily compared to an FDM (Fused Deposition Modelling) technology; with the difference that here concrete is extruded instead of plastic. The concrete is pumped and pushed through a nozzle at a constant speed. A large computer controlled 3 axis steel gantry system deposits this concrete with high precision layer by layer (Fig. 2).

The concrete is deposited without the use of any formwork. Therefore the process allows for an unprecedented freedom in geometrical complexity. As the parts are printed, every single printed part can be different and customised.

## THE WALL COMPONENT

To demonstrate these functionalities of additive manufacturing, a wall component was designed and constructed. This component tried to address the new geometrical freedoms that can be associated with additive fabrication. The design for the wall has a varying thickness that can be optimised to local loads. There are also cavities in the component that can incorporate services and locally optimised insulation and reinforcement. Due to the geometrical freedom, local optimisations can be achieved through differentiating geometry. (Fig. 3)

By developing this prototype it became apparent that current standard CAD tools were not sufficient. The freeform construction process extrudes concrete in beads with a typical diameter of 9mm. This is about 100 times larger then current commercially available smaller scale rapid manufacturing processes. With this process the actual extrusion parts become visible and can even be seen as part of the aesthetics of the part. It is therefore crucial that these paths are taken into account when designing for this large scale additive manufacturing process. (Fig. 4) Various experimental extrusion paths were explored as part of a graduation thesis at the Architecture and Urban Design Department of the University of Gent (Bernaerdt, Van Hauwaert and De Kestelier, 2009). These path designs were not developed to optimise for the manufacturing process, but to explore possible design expressions. (Fig 5. & Fig. 6) In most additive fabrication techniques material is added through horizontal layers. This means that tool paths are in fact only in two dimensions. These studies show that there might be possibilities to explore more complex 3 dimensional tool paths. (Fig. 7)

Taking into account the lessons learned at the University of Ghent, a parametric model was set up in Generative Components to produce the wall component at Loughborough University. It came apparent that a traditional method of modelling, even parametric solid modelling was not going to be sufficient. The design did not only have to define the external volume of the wall but also the actual tool path. The machine tool path became an integral part of the design (Fig. 8 & Fig. 9) The manufacturing process is embedded into the core of the design environment. The tool path model became the parametric design driver as the manufacturing constraints were programmed within that tool path. (Fig. 10) Slight changes in width of the extruded concrete could for example be easily adapted into the parametric model.

**Fig. 4:** The concrete extrusions are visible and part of the overall esthetics.

**Fig. 5:** Design explorations of different tool path options.

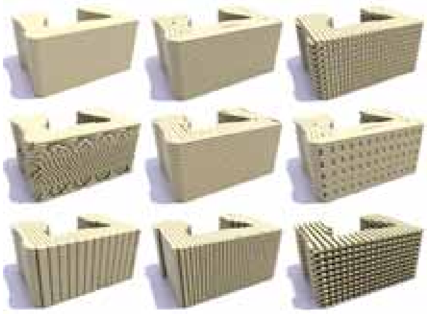
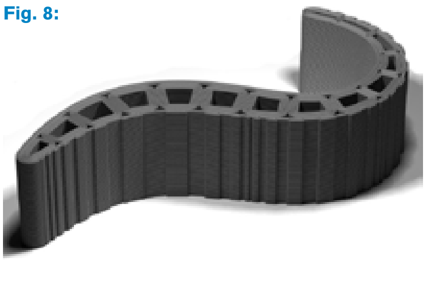


**Fig. 6:** Design with continuous, uninterrupted tool path.

**Fig. 7:** Explorations with 3-dimensional tool paths.

**Fig. 8:**



Creating the tool paths in a parametric model was not sufficient as it did not visually represent the design. Therefore each of the tool paths had to be converted into extrusions. This model was then also 3D printed through with a Z Corp. printer.

The workflows for most additive fabrication technologies are quite similar. Typically a design would get modelled up in a 3D CAD package with preferably a solids modelling engine. This 3D model is then converted to an STL file. This file format is the standard file format for most additive fabrication processes. An STL file is a very simple low level file format that stores geometry as a simple set of triangles. Depending on the technology, the STL file will be sliced into horizontal slices. Each of these 2D contoured slices will then have to be filled up and constructed by the additive fabrication machine. Each additive fabrication technology will have its own way of generating a set of machine codes to construct and fill these contour slices. (De Kestelier and Peters, 2008)

For the wall component no STL file was generated. The Generative Components model was constructed with tool paths in mind. A set of lines is still not enough information to generate G-code, which could drive the concrete printer. This G-code is a numerically controlled programming language that is widely used to drive CNC machines. To generate this G code for the concrete printer, a separate software tool was written to convert the line geometry that was generated in generative components into a set of machine instructions or G-code. (Fig. 11) (Bernaerdt, Van Hauwaert and De Kestelier, 2009). There was no intermediate step needed to go from the 3D model to a set of fabrication instructions. The fabrication technology was embedded within the 3D model and the design process.

This process is off course only possible when the designer understands the fabrication technology in detail and when there is a constant interaction between the designer, engineer, programmer and fabricator. It is clear that the development of a new design environment that can embed the possibilities and constraints of additive manufacturing will be crucial in the development of this technology. (Fig. 12)

**Fig. 9:**

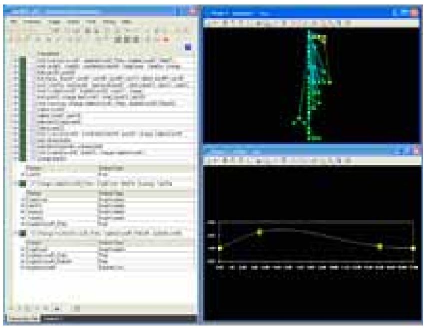


**Fig. 10:**

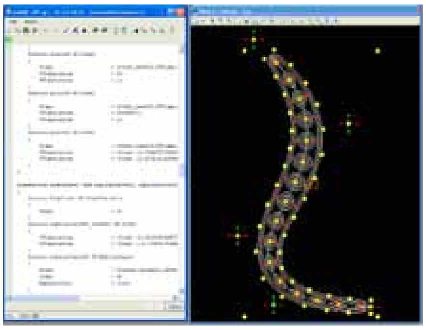


**Fig. 11:**

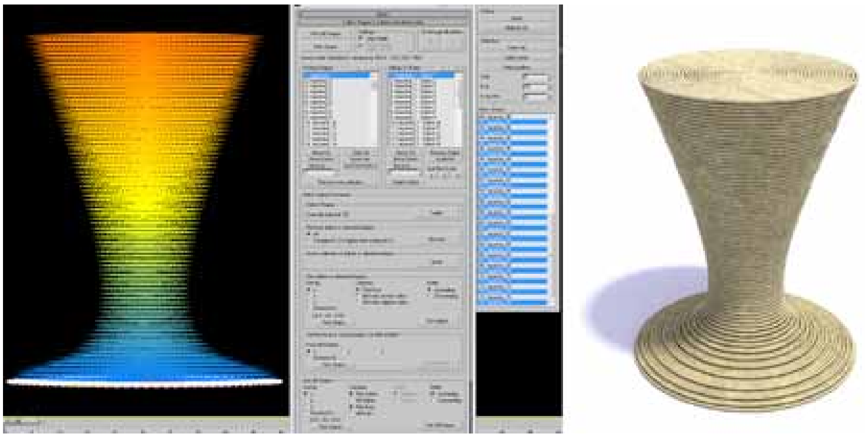
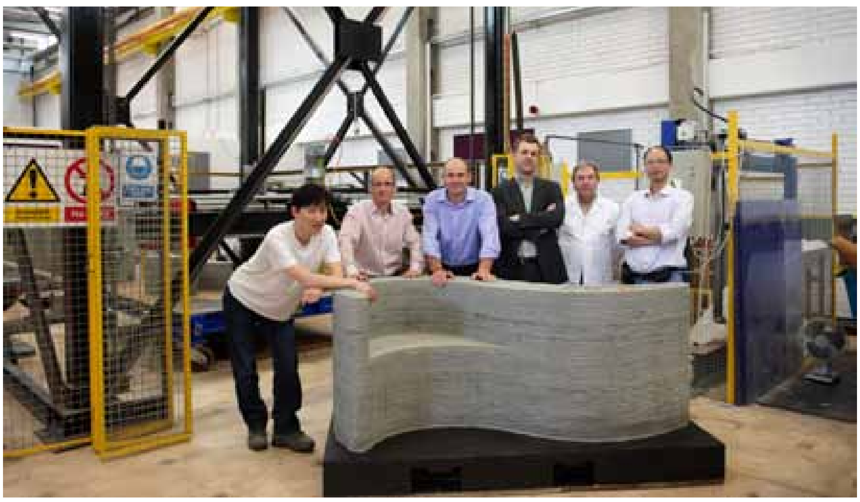


**Fig. 12:** The research team consisted of designers, engineers, programmers and fabricators.



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