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ANYTHING, ANYONE, ANYWHERE

Toward a cloud-based 3D printing fabrication in architecture

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Abstract. According to Hod Lipson at Cornell University's Creative Machines Lab, *cloud manufacturing* 'consists of a network of small-scale, decentralized nodes of production.' It is a novel production approach relative to centralized mass production and standardisation methods common to today's industrial processes. To date, cloud manufacturing techniques have focused largely on the production of small-scale consumer goods that integrate digital fabrication techniques, the most popular being 3D-printing technology. With advances in network-based design platforms for 3D-printing services in combination with the global installation of fabrication laboratories (fab lab), the production of architectural building components using cloud manufacturing techniques is now possible. This paper will define how cloud manufacturing techniques can be expanded into the realm of architectural practice and, in particular, how such techniques can be applied to larger-scale building and construction components. The paper will further discuss how such novel *additive manufacturing* (AM) processes applied to construction can potentially revolutionize architectural design by generating a new collaborative design model that facilitates local production of customized and readily assembled building components on demand.

Keywords: additive manufacturing; cloud manufacturing; peer-to-peer production; collaborative design; open-source design.

1. Introduction

Ubiquitous network access has characterized the past 20 years and is today redefining the way we work, design, and consume products. Combined with the actual capacity to share objects over the Internet (Gershenfeld 2005), it could change the way we build, using a novel approach to design and manufacturing: *cloud manufacturing*. In a 2012 special report on manufacturing and innovation, *The Economist* proclaimed the advent of what Jeremy Rifkin called the ‘third industrial revolution,’ i.e., the shift from mass production to *collaborative manufacturing*. Also known as *intelligent manufacturing* or *cloud-based design and manufacturing* (CBDM), this non-linear process integrates digital design and robotically-driven fabrication via an online interface centred on users that facilitate access to customized design. According to Wu et al. (2013), cloud manufacturing "refers to a product realization model that enables collective open innovation and rapid product development with minimum costs through a social networking and negotiation platform between service providers and consumers. " Recently, new economically viable design and manufacturing models have been developed for the production of small consumer goods and accessories, reflected by the popular websites Ponoko and Shapeways (Anderson, 2012).

In architecture, the magnitude and complexity of design projects have long prohibited such practices. Unlike digital design, automated fabrication is dependent on the size and specificity of machinery that cannot be scaled-up. Most projects related to digital fabrication result in small prototypes and installations that take months or years to build, a timeframe that includes the design process (programming of parts and assembly), and the construction process (material used, fabrication technology and transportation).In terms of complexity, architectural design primarily relies on the ability of manufacturers to integrate new parameters with their available machinery as well as the level of skilled labour to operate such machinery. It explains why architectural design is still produced according to manufacturers’ product specifications and building standards and avoids customising every component. With *computer numerical control* (CNC) tools, fabrication complexity is redirected toward the machine, yet the program that transfers information from the model to the robot requires even more specialised workers. In this context, digital fabrication remains expensive and out-of-touch with architectural practice. It is confined to experimental architecture or, at most, a luxury product.

Relying mostly on CNC machinery to subtract contoured shapes from standard material sheets, advanced manufacturing techniques are now integrating *additive manufacturing* (AM), a technology that enables layer-by-layer 3D-printing of any shape in a single machine, using composite material as a medium. Although used for prototyping for more than 25 years, AM has just recently started to gain popularity in research as a mean to produce architectural components such as cladding, acoustic panels, partitions, functional walls and furniture. The new hype it has caused (that can be found in any number of design blogs and conference presentations) has led to an unusual movement in the search of ‘printing’ the largest components or building assemblies (and in some cases the entire structure), a scale that to date most 3D-printing manufacturers has yet to achieve. The technical challenges are enormous. AM is still confined to small objects due to slow production, high data processing demands, resolution and overall dimensions that a single machine can manage (Hopkinson, et al., 2006). However, by merging cloud manufacturing with 3D-printing technologies, the capacity to simultaneously produce multiple parts through a distributive network of fabrication hubs may yield a new design model that could unlock the potential of AM in architecture. This paper will demonstrate how these combined technologies could enable the fabrication of almost anything by anyone, anywhere in the world.

2. Anything

Because it enables a higher level of detail and greater freedom over the geometry and complexity of form within a single material, 3D printing has sparked a whole domain of research that can potentially transform the design and construction process in architecture. Before the advent of AM, few processes were able to yield fabrication logistics (physical) with greater ease than what could be accomplished throughout the design phase (virtual). As a result, *design for additive manufacturing* (DfAM) is oriented toward modelling almost ‘anything.’ However, AM technologies for large-scale components introduce new design constraints that affect directly the manufacturing time (Lim, et al., 2012):

- The surface quality of building components;
- The limitation of geometric freedom (overhangs and member size); and
- The weight of the part.

The most critical constraint that affects the above list is the resolution that defines the matrix of density a printer can produce. It constitutes a powerful tool for the designer to retain control over the quality of the resulting object. A coarse resolution results in thick layers and affects the quality of the part. Improperly identified, it can jeopardize the structural integrity of the part, as demonstrated by the Freeform Construction group experiments at Loughborough University (Le, et al., 2012). Another consequence of an inaccurate resolution is the inability to generate small member size and therefore restrain substantially the degree of design freedom over the geometry. Furthermore, with a higher resolution, large components can optimize the material distribution through local densities, i.e. an optimisation routine using finite element analysis (FEA) to reduce the total volume of material without affecting the global structural integrity. Thus, the object is lightened and the manipulation and transportation is greatly facilitated.

From the manufacturer's perspective, a high-resolution printed part contributes to reduce the time necessary to post-process the final product as it appeared in Enrico Dini's work '*Radiolaria*' produced with his D-Shape technology. Also strongly constraining for large-scale building components is the production of support material, essential to maintain a high degree of freedom over the form, that is harder to remove without breaking the part (for both binder printing and extrusion-based methods). The viability of large-scale 3D-printed objects, considering the previous constraints, resides in the discretisation of large architectural components into smaller parts, with the integration of assemblies directly in the geometry as part of the design phase.

A distributive manufacturing system, when it contains several members, can produce quickly many parts in a very short period of time and guaranty high-resolution architectural components delivered from local small factories or micro-entrepreneurs. However, the cost of professional 3D printers can be prohibitive, and the technology is not designed for large-scale building components. In the past decade, innovations have spurred from the architectural community in an attempt to develop AM technologies suitable for construction. Since most AM systems are developed as do-it-yourself (DIY) kits, they are easily replicable. Most already integrate open-source microcontrollers, such as Arduino (open-source physical computing), to control material extrusion or deposition, and they rely on generic robotic equipment. To date, few experimental designs and research projects have proposed innovative construction processes for large-scale AM in the field of architecture using plastic materials (Phantom Geometry (2012), Kamermaker (2013)) and ciment-based materials (Contour Crafting (2004), D-Shape Technology (2007), Freeform Construction (2008), Digital grotesque (2013)).

One known method used to facilitate and expand the application of novel technologies is the use of an open-source system based on three criterions (Anderson, 2012):

- **Repeatable**: Easily replicable by providing the specific hardware and its operating software (including tested settings) for small entrepreneurs offering manufacturing services;
- **Transformable**: Accessible by allowing modifications to the current version and fixes to current glitches; and
- **Publishable**: Promote a community of users to share results and discoveries.

This model is based on the RepRap project (Replicating Rapid-prototyper), a well-known experiment launched in 2007 by Adrian Bowyer at Bath University. The project's goal was to replicate itself by printing its own parts. It is also a wiki meant to evolve through information sharing. As a result, the 3D printer became the most affordable in the industry. It has also garnered much attention for the *makers* community while promoting AM innovations outside academic circles, the most popular being the development of the Makerbot following the RepRap model. After only five years, RepRap and its derivatives still own the largest share of the market, according to the Wohlers Report 2012.

An experiment conducted at McGill University revealed the possibility of producing such open-source hardware, using digital fabrication and microelectronics adapted for use with an industrial robotic arm (Fig. 1). *Fused deposition modelling* (FDM), the technology used for the project, is a process that melts PLA filaments. In order to adapt the technique to larger-scale components, an AM robot end effector is mounted on a robotic arm. It can generate 3D printed objects up to one meter cube. The 3D printer attachment allows a CNC router to run concurrently, making it possible to alternate between milling and 3D printing. Although parts that comprise the extruder (nozzle, moult extruder, step motor, and Arduino board) are generic and accessible from 3D-printing Internet forums, the brace attached to the robotic arm has to be designed in-house.

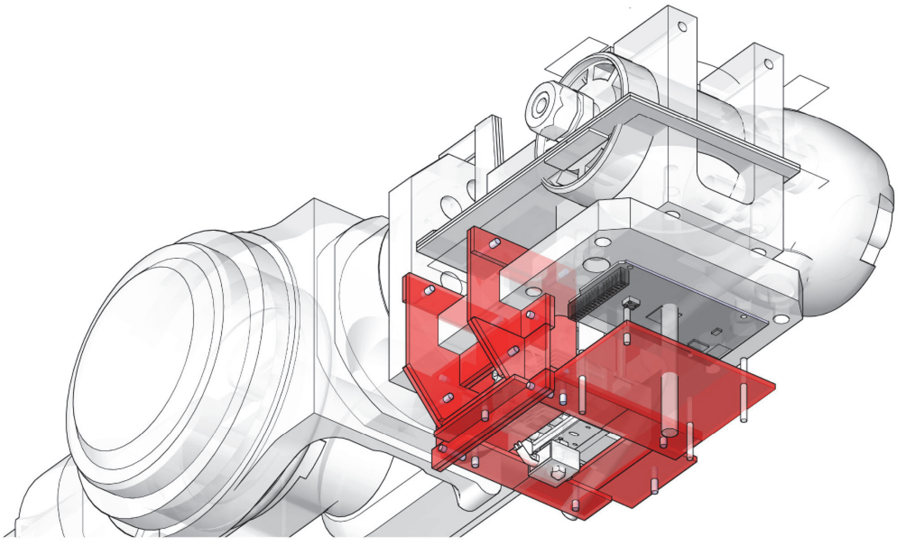

Figure 1. Open-source 3D printer mounted on a robotic arm

3. Anyone

With AM, less time spent on design to meet manufacturing constraints (tolerance, assembly, coordination between specialists, etc.), representation (technical drawings), and prototyping means more time allocated to the design process and the customization of products (Chua, et al., 2003). Furthermore, since a single large-scale 3D printer can fabricate a quasi-unlimited variety of geometry, customizing production does not add additional costs. The absence of part-specific equipment (such as moulds for plastic injection) means no economy of scale. Design for additive manufacturing, in point of fact, is centred on the object and the design process. It makes it possible for designers who do not master manufacturing processes to generate or modify new designs with very little consequences.

The growing popularity of desktop 3D printers reveals a new fabrication paradigm, one where 'anyone' can fabricate manufactured objects, even at home. But considering the aforementioned constraints specific to large-scale AM, the design process requires in most cases additional expertise. The Internet-centred cloud manufacturing offers an online platform for the interaction and exchange of information between designers and manufacturers, and the designers themselves. With increasing user-friendly web platforms, new collaborative design models allowing for the customisation of objects centred on user experience are emerging.

Collaborative design is a concept based on the improvement of the design experience through the participation of multiple actors – designers, customers, and manufacturers – that together form an interdisciplinary force to solve problems. Cloud-based design and manufacturing web services revolves around sharing resources and services through virtual interactions. According to Wu et al. (2013), collaborative design models form two groups: web-based design (co-design) and agent-based design (collaborative design).

3.1 CO-DESIGN

Co-design empowers designers and architects to develop and improve specific products by way of some level of customisation in conjunction with the manufacturer. Using an interactive website, users can modify and adapt generic object settings to define personalized design while being guided by parametric settings through open-GL rendering (allowing real-time visual feedback). Made possible by the recent development of cloud-based applications and open-source software (e.g. Blender), co-design allows users to interact with the designed object directly on the web by adjusting its parameters. The source is a directory available on the manufacturer website. There is no need to purchase software; only an Internet connection is required. This approach is beneficial for both user and designer. First, it releases the designer from the burden of coordinating and *versioning* (producing several iterations to meet user needs) and places the user in the centre of design and manufacturing. Second, the user is fully integrated into the design in real-time, proffering feedback through a user-friendly interface. When completed, the customised product "can be manufactured in a regional facility near customers' homes to save on shipping costs, delivery time, and the environment" (Lipson & Kurman, 2013).

However, most of the examples in architecture (e.g. Opendesk, Wikihouse) concern subtractive manufacturing, a technology that is widely available. Since AM for large-scale architecture has not yet provided a solid and replicable technology, and that the scale of the components required structural reliability and quality assessments from a professional, co-design seems not appropriate.

3.2 COLLABORATIVE DESIGN

"Collaborative design is focused on helping designers generate creative ideas and collaborate more efficiently and effectively by sharing design and manufacturing resources and services through formal and informal interactions" (Wu et al., 2013). Different from web-based design, collaborative design and collective innovation (also known as crowdsourcing) imply a more profound engagement from divers professionals and designers looking at solving similar problems. The core concept is to allow selected members or every user full access to models and codes. Similar to GitHub, a web-based service for software development, it offers the possibility to create both private and open-source directories of objects that can be readily fabricated or redesigned for customised use. The blogging platform of the plugin Grasshopper, graphical algorithm editor, shows the benefits of sharing models and solutions through virtual interactions. The workload is shared, and collective innovations make it faster than traditional methods.

In architecture, copying and modifying is often part of the design routine. Although each project is customized for a specific use, most details and construction information remain similar. Keeping all models private puts an unnecessary workload burden on the designer. One novel way to outsource the production of architectural solutions is to share models and information with a community of designers and engineers on an open-access web platform from which to post, copy, modify, distribute, re-post, re-modify, and redistribute. When applied to the complexity of parametric design and AM, open-source projects can quickly be made available to anyone.

Architecture can be both an open-source product for anyone to use and a highly manufactured product responding to the latest requirements in sustainability, performance, and quality (Parvin 2013). In an attempt to make design complexity accessible to anyone, the WikiHouse project explored this form of collaboration. Created by Architecture 00:/, this non-profit project initiative is an open-source construction set that aims to provide basic shelter entirely made from CNC-milled plywood, following principles of digital fabrication. Owing that it uses a single material coupled with an inexpensive production tool, it streamlines design and manufacturing processes, making it easier, faster, and cheaper. Furthermore, its parametric settings facilitate other users to further modify and customise the model and its fabrication.

Additive manufacturing for building components is still in its infancy and could benefit from cloud-based design and manufacturing organisation. The growing hype towards 3D printing combined with the new forms of virtual interactions, human-computer and human-human, could generate quickly new forms of design and construction. Figure 2 is a synthesis of the different stakeholders involved in cloud manufacturing from the website *opendesk.cc, ponoko.com, shapeways.com, 100kgarages.com and fabhub.io*.

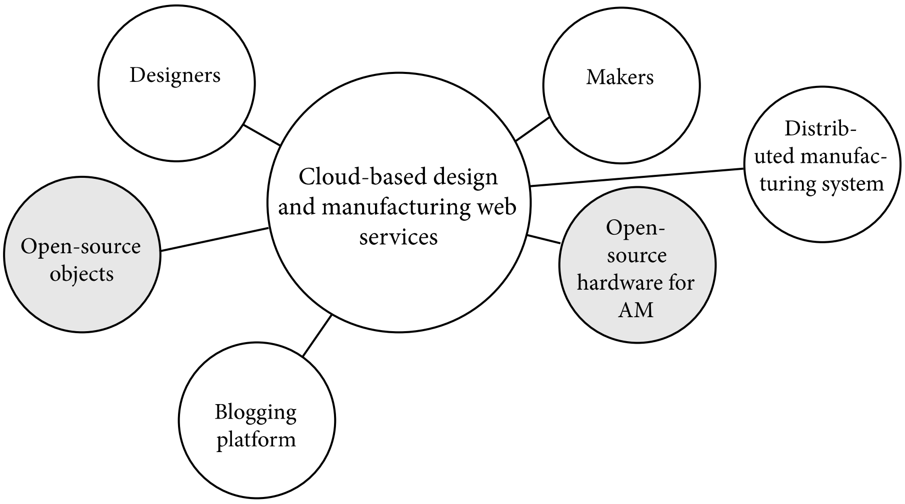

Figure 2. Cloud manufacturing for large-scale AM

4. Anywhere

To complete the picture, 3D-printing technology open-source hardware and open-source design platforms require access to manufacturing resources that are geographically close to the user. The core concept of cloud manufacturing resides in the availability of resources required for design and production of products that are connected through a network of online manufacturing service providers.

Distributed manufacturing can optimally redirect any order placed through *knowledge management systems* (KMS) via an algorithm that organizes and optimizes the workload of each node of production. To be effective and provide services near to users, the network of manufacturers must connect to a critical mass of small workshops using similar technologies, which has not as yet been achieved by large-scale AM technologies. However, this model has enormous potential as demonstrated by the popularity of cloud manufacturing providers, such as Ponoko and Shapeways. It being a New Zealand-based online service for manufacturing companies founded in 2007, Ponoko serves as an intermediatory between users and makers. Its success shows the growing interest customers have in buying online digital designs for small objects and accessories (Anderson, 2012).

As an example of a forthcoming cloud manufacturing initiative for larger products, FabHub is a web platform that locates small manufacturing shops that can process digital information for the manufacturing of goods. Mostly comprised of small fab labs, FabHub offers a complete set of digital fabrication services, such as CNC milling, laser cutting, 3D-printing, etc. It is as yet far from the intelligent manufacturing model it plans to be, but it illustrates an effort to implement an alternative to centralized manufacturing.

5. Challenges and opportunities

While most 3D printed objects today are small and have no noteworthy structural requirements, it is possible that the adoption of AM for architectural components could lead to failures that threaten the security of users. Who is liable if a product fails? It is important to involve professionals (such as structural engineers) to make certain that products conform to building codes, standards, and regulations (a process implemented by the WikiHouse project), that, in effect, no failures will lead to hazards or risks that threaten the security of users. This is even more important for a collaborative model (as previously explained) that involves non-professionals or non-qualified designers (architects rather than engineers). Not only does the design object need to be validated, the hardware needs to be as well. To be successful and garner trust, open-source hardware and objects need supervision in a similar manner to control any possibility of faulty information.

Foreseen are further developments in mobile and autonomous AM technologies that will better suit construction industry practices. The KamerMaker project proposes to build a whole façade in Amsterdam by 2015 that uses a portable large-scale 3D printer directly onsite. Even more radical, Markus Kayser proposes an ‘off-grid’ 3D printer that could print anywhere with total autonomy, using sand as raw material to build melted silicate components.

Together, cloud manufacturing and AM could completely revolutionize our approach to design and architecture. It could democratize digital architecture and fabrication for anyone almost anywhere and provide architects and designers the chance to offer high-end design to those who cannot afford it. It also has the potential to change and adapt quickly by way of collective innovation to social and environmental changes, making designers important future social actors in our built-up environment.

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