

3D Printing For General Contractors: An Analysis of Potential Benefits

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The industry of 3D design and printing is in a state similar to when the first desktop computers were marketed to the general public. The possibilities of the emerging technology were limitless then, but nobody knew exactly how it would affect every day life on a global scale. Today, we are certain the 3D manufacturing process will change as different methods are experimented with and developed. The challenge with 3D printing in the construction industry is integrating this technology with decades old building procedures. Just like all great endeavors, there is a process of trial and error that will likely take decades to achieve standardized building methods with large scale printers. The first objective of this paper is to study the numerous technologies that currently exist and understand what factors are most likely to influence the construction industry. The second objective is to introduce the current 3D printing technologies and how they can be utilized to improve current business practices. By understanding these two facets, the general contractor can begin to consider the affects 3D printing will have on their company.

Keywords: 3D Printing, Construction, General Contractor, BIM, MEP

Introduction

"The first working 3-D printer was created by Chuck Hull of 3D Systems in 1984. Currently, there is a $1.7 billion market for 3-D printing. By 2015, that number is expected to double" (King, 2013). The 3D printing industry is growing, but it is difficult to predict just how or when the construction industry will begin to be influenced. This paper intends to explore how this may happen by focusing on two concepts. First is to examine the technologies that have the greatest chance of being utilized in common large scale building systems. The second is to explore ways by which a General Contractor (GC) today can utilize in their own company to improve efficiency and competitiveness. Since design primarily relies on the architect/owner, and product development is primarily within the subcontractor's scope, the GC must wait until the opportunity to use 3D printing in a building application presents itself in a bid package. This is not a common project delivery method; however, there are smaller applications where a contractor can use 3D printers to become more productive. At the present time, the only functional use of 3D printers for a GC is in their BIM division.

It is important to understand the capabilities of a 3D printer in regards to creating a model that has the functionality for what it is intended to be used for. "As 3D printers have become more capable and able to work with a broader range of materials, including production-grade plastics and metals, the machines are increasingly being used to make final products too. More than 20% of the output of 3D printers is now final products rather than prototypes, according to Terry Wohlers, who runs a research firm specializing in the field. He predicts that this will rise 50% by 2020." (The Printed World, 2011). As a general guideline of what to expect when ordering for a print to be made, a typical model can take 30 minutes to a number of days to print depending on size and density. The cost ranges anywhere from hundreds to thousands of dollars depending on material, size, density and whether color is incorporated. In any one of the scenarios above, it will take generally around 12 hours to print something at a presentable scale, around 12"x12". The overall cost of the 3D print model will depend on whether it is outsourced to a 3D printing company or it is done in-house. It also depends on the detail of the final 3D print. For a more detailed model or a model outsourced to a printing company that incorporates a fee, the time and price increases substantially. These variables must be taken into account based on the overall duration and budget for the project.

The Software

Computer code that controls 3D printers are being developed utilizing existing 3D modeling software which is then adapted for the printer. The applications are user friendly and easy to understand for simple designs. However, more efficient computational techniques are necessary for tailoring complex structures for much larger components with highly intricate internal structures (Seepersad, 2014). Once the design has been created in the modeling software, the file is exported to the 3D printer's software as a hard graphic image. There is a high degree of compatibility among the available digital 3D modeling software packages and the printers. The major software companies have already begun integrating 3D printer support into their popular design software. The process for creating a 3D print out of a BIM model starts by saving the model into a specific file that is compatible for the printer. All functionality is removed from the individual image parts, however, the model as a whole can be manipulated for size, scale, density and orientation for the printer. The printer company could provide their own software, or there are open source programs freely available on the internet. Major companies like Autodesk are beginning to roll out software packages specifically for 3D printing capabilities. Ultimately, the improvement and standardization of the software is out of the control of the GC. All large scale general contractors now have a BIM department to handle the electronic issued A/E designs. As it is the job of the GC to check for constructability of the design, a 3D printed model must go through the same process to detect potential failures and clashes with other building components. The key question for the GC is not what software to use, but rather who is capable of using the software. Currently there is a shortage of competent building information modelers in the construction industry and the demand for them will grow exponentially over time (Azhar, et al.). The problem is compounded due to the novelty of 3D printing. Whereas the software is relatively easy to implement, it is a difficult decision for a company to buy into the unknown cost to develop the skills of their personnel.

Print Methods For Construction

The printers' potential for further development, for construction or otherwise, is bound to make a significant impact to the current market place. It is estimated that 3D printing could generate economic impact of $230 billion to $550 billion per year by 2025. The largest source of potential impact would be from consumer uses, followed by direct manufacturing and the use of 3D printing to create tools and molds (Manyika, Chui, et al., 2013). A major indicator for the direction where printer development goes depends on proven standards created within the industry. "As a response to the need for standardization in the field of (Additive Manufacturing), a number of initiatives on a national and international level were launched. Amongst others, ASTM and ISO have established technical committees for the development of AM standards" (Darmstadt, 2013). It has been cited by a number of news and investment publications that with the expiration of patents in the coming years, a rush for the rights to the technology will be seen similar to the dot-com era of online market expansion. The direction these patents take the 3D printing industry is important for future large scale machines because the heavy investment required to build them will be scrutinized for possible infringement of other technologies. This poses a risk to develop and sell a printer that works similarly to a printer produced by any corporate entity trying to capitalize on profits. It is largely a job for government and legislatures to simultaneously facilitate technology growth and protect intellectual rights. "The challenges for policy makers include addressing regulatory issues – such as approving new materials for use – ensuring appropriate intellectual property protections, and assigning legal liability for problems and accidents caused by 3D printed products" (Manyika, et al., 2013). This is important for a GC to understand some of the market constraints, as well as to protect themselves in the litigation-heavy world of construction.
The two primary methods of 3D printing of objects on a scale of a habitable building are Extrusion Deposition and Granular Materials Binding. Other methods involve using spray polymers, lamination, and laser micro-fabrication but these are not as well suited for the intent of building construction. They do not have the same ability to produce large-scale structures with widely available material. This may change in the future as methods advance or are combined. The majority of attempts to create a complete structure have been by means of the methods described below.

Extrusion Deposition is the process of pouring a product through a nozzle as a liquid where the product cures enough before the next layer is placed on top. The most obvious form of this would be concrete with the objective of building a wall, for example. Ignoring the requirements of rebar or a specific finish, this method can print the outline to any degree of curvature. As the wall is built up, each layer can overlap by a specific degree to change the vertical angle of the wall. Supports are required if the layer exceeds the maximum offset, which can be built into the model then removed when the wall is finished. The modern methods of building a form by hand would be difficult to achieve the accuracy and complexity of curves in a concrete design. Other possible materials are thermoplastics, eutectic metals (capable of solidifying quickly and at an appropriate temperature), and plaster.

Granular Materials Binding is a system by which a thin layer of product is laid down, and then a binding agent or a sinter is applied in the pattern of the model. This process happens repetitively until the model is complete, then the loose product is removed to reveal the model. The benefit of this method is that any shape can be created since it is supported in space by the unsolidified product. Although this may not have the same potential to quickly build structurally minded objects, it allows the designer virtually unlimited freedom to print any object they can conceive. Common products that can be used are metals such as titanium and stainless steel, thermoplastics, ceramic powders, and plasters.

Developing Technologies and Hopes for the Future

Large scale 3D printers have a long way to go to become as efficient as the refined manufacturing methods of today's building materials. If a GC is to consider 3D printing, whether now or in the future, it is important to understand their primary strengths and weaknesses. The advantage of today's printers over current fabrication methods is the ability to create dimensionally accurate objects that takes exponentially less time and cost to create than hand built methods. This makes sense for individual items like furniture, counter tops, and nonstructural finish building components. Some of the benefits of additive manufacturing techniques include ease of prototyping, significantly increased geometric complexity, and extreme design versatility (Snyder, 2014). As a designer, the ability to add architecturally unique qualities around a basic design becomes automated. As a contractor, the constructability of an architectural feature that previously was extremely difficult to create is now more predictable. However, the technology for anything beyond simple objects is currently limited. Within each of these technologies there are abilities and limitations, but none have all the attributes of a complete building system.

Figure 1 lists a number of research institutions and private entities with their associated specialty in the field. They are researching the core theories currently being developed to eventually achieve a fully functional building system. The current media attention is on "the first 3D printed house" stories, but these are merely prints in the shape of a house with material that is suited for the printer, not a habitable structure. As technology progresses and the categories in the representation slowly change from "no" or "in theory" to "Yes", the links will develop among the separate systems. The most impactful categories for a GC are "Process capable of delivering components large enough for building structures" and "Research of build-in materials and specialists' applications". These two categories implicate that the system is capable of both building and incorporating mechanical, electrical, and plumbing into the structural design. While much of this is still "in theory", understanding how this technology develops may have an impact on how the subcontractors develop their own operations to adapt to the technology.

Figure 1 - Heat Map of Identified Most Progressive Research Groups (Fisher et al, 2013)

Research Leader	University	Name of System	Process capable of delivring components large enough for building structures (walls, slabs)	Maximum size of a 3D printed element	In process of solving/solved automation/robotics system	Possibility of a building segment customization	Material properties and processcharacteristics need to be an integral part of new delivery systems	Possibility of adding new functionalities to standard building fuctions	Research of build-in materials and specialists' applications
Khoshnevis	USC	Contour Crafting	Yes	Walls, slabs/curved surfaces in theory	Yes	In Theory	No	In Theory	Yes
Bechtold	Harvard	3D Printed Ceramics	No	Louvres, tiles	Yes	Yes	No	In Theory	Yes
Buswell, Gibb, Thorpe	UK Loughborough	Rapid Prototyping	In Theory	Standard building blocks	Yes	In Theory	In Theory	In Theory	No
Enrico Dini	Private Sector "Monolite UK"	D-Shape "Robotic Building System	Yes/In Theory	Walls/slabs/curved surfaces - not completely successful	Yes	Only in comercials	Only in comercials	Only in comercials	Only in comercials
Oxman	MIT	Material Based Design Computation	No	3D printed desktop sized segments	No	In Theory	Yes	Yes	Yes
Bao & Cui	Stanford	Unknown	No	Nanoscale structure	No	No	No	No	No

Benefits to a General Contractor Today

Everything discussed so far has dealt with the 3D printing industry's influence in the construction industry. What is likely more of interest to a GC is the applications with current printer capabilities that can be used to improve business. Three primary benefits for a general contractor include using the printed 3D model for:

1. Job proposals
2. Field coordination
3. Product compatibility

Job Proposals

The objective of any contractor should be to provide to the owner the best value with their knowledge and planning of the project. The success relies in part on satisfying the following items during the proposal stage (Frey, 2012):

- Expand on the essential information about qualifications and experience
- Reflect current A-E disciplines, experience types, and technology
- Eliminate duplicate information
- Eliminate information of marginal value
- Facilitate electronic usage of information

A 3D model can facilitate this dialogue by the essence of what a model is. Aside from the basic capability to design and produce the model, it validates the thought process of working through the drawings and details. The ability to accurately develop and print the model from paper drawings demonstrates the knowledge to make interpretation of the design, even when they are not 100% construction documents. Talking points during interviews can be directed to specific deliverables, rather than circulating around vague management strategies. Having this model highlights the contractor's deeper knowledge of the project and is impressive to any potential client.

Design-build contracts may rely on the contractor to propose multiple designs or alternate designs. Providing multiple models with pricing options can be a powerful tool in giving the owner options to pick a design they can be happy with. This is especially helpful when the decision relies on the approval of multiple people, many of whom are unlikely to have the experience to grasp the full design intent from 2D documents or digital models alone. Especially when time is a factor, a printed model can help the owner make a selection more quickly than by using drawings and relying on the owner to decipher the design. This is not common practice now, but as BIM departments mature, the ease of designing and printing models can be a fast and cost effective way of communicating a proposal to the owner.

Field Coordination

As the construction industry is further digitalized, communication relies increasingly more on AutoCAD drawings, emails, and cloud information distribution. This removes the subcontractors and superintendents from the kind of hands on collaboration that was once required to plan work. The following observations were taken from a site where a model "floated" around the conference rooms. On a high-rise project in downtown San Francisco, the fast pace project required numerous meetings on a daily basis between the owner, design team, and subcontractors, inspectors, and other related entities. The project team consisted of approximately 30 professionals from project managers, superintendents, and project engineers which required its own internal coordination. The 3D model, which was of a 10"x10"x12" size made for a wind study, was routinely passed around as a way of describing the topic of conversation. In addition, during routine weekly meetings to coordinate logistics and work areas, it was easier to work with a 3D model than with 2D prints when navigating a digital model. Anyone who has ever tried to give a presentation and had technical difficulties with their computer understands the inefficiency of having a room full of people waiting for computer files to load. By utilizing 3D printed models in the office, someone can simply point with their finger to address the location and scope of the work they are referring to. Also, anyone with little to no knowledge of a project's drawings can understand the general topic of discussion. A simple model in the conference room that can be passed around and shared has been shown to be beneficial during all types of planning and discussion such as:

- Logistic coordination
- Scope gaps between contracts
- Analysis of drawing details

- Technical studies for lighting, wind, utilities, etc.

To further improve the efficiency of project flow, lines of communication must also be maintained with the design team and owner regarding any changes or impacts from the constructability standpoint. According to Ku, K.H., "Ideally, each project team member would contribute his or her specialized knowledge of cost, technical feasibility, performance, and various other project constraints and requirements. However, each party is constrained by their organizational rationality and their information-processing capability. Thus the key to collaboration of this type is that effective geometry control procedures must exist to incorporate the technical issues without sacrificing the architect's design intent." (Ku, K.H., 2005) The concept that the architect's objective is to achieve a certain design while the contractor's objective is to meet the design through means and methods relies on the ability to see issues on the same plane. 3D prints are a tool the project team can leverage to find middle ground between design intent and constructability – something that is not as easily accomplished by using 2D construction documents.

Product Compatibility

Rapid prototyping is perhaps the most widely used way of utilizing 3D printers in all industries. This topic itself is the subject to much research attempting to understand the cost and time gains associated with rapid prototyping. "A key issue regarding the investment in casting process is the production of the expendable pattern in the case of a prototype casting, for which the traditional aluminum-alloy die is uneconomical. Rapid prototyping techniques can meet this requirement, producing single/few parts in short times and without tooling costs." (Bassoli, E., et al., 2007) A contractor would use the prototyping process in much the same way as a typical product design, going through multiple iterations until a suitable design can be agreed upon. Whereas in the past, this was a necessary high investment proposition with hopes of high long term returns. Now the returns can be realized within the time duration of the pre-construction phase.

Construction is fundamentally the process of assembling materials together in the most efficient way possible. This creates risk due to the high level of variability in the building process. The quality control program can be enhanced by the testing of the most critical components, especially for waterproofing and space constraints. 3D printing can test the details of a design prior to fabrication and installation. Similar to product samples which are common, it can be a requirement to provide accurate working models that prove the effectiveness of the design in a working scale. This is especially useful for collaboration among architect, contractor, and subcontractor when constructability is an issue.

One of the most useful applications of 3D models for testing is to prevent water intrusion, as this the highest long-term risk for any GC. The successful integration of roofing systems, glazing, caulking, flashing, and exterior wall systems is always a critical challenge for project. Being able to prove functionality is especially important when warranties and the high cost of repairs are dependent on the performance of custom or specialized building materials. Other supplemental steps can be taken to test space requirements or constructability. While BIM is an extraordinary tool for managing space, 3D printers can go beyond in providing hands on models for unique or challenging installations. This is similar to a mock up, but for the hidden spaces above ceilings, in wall, or below ground systems where normal tools and installation methods will not work.

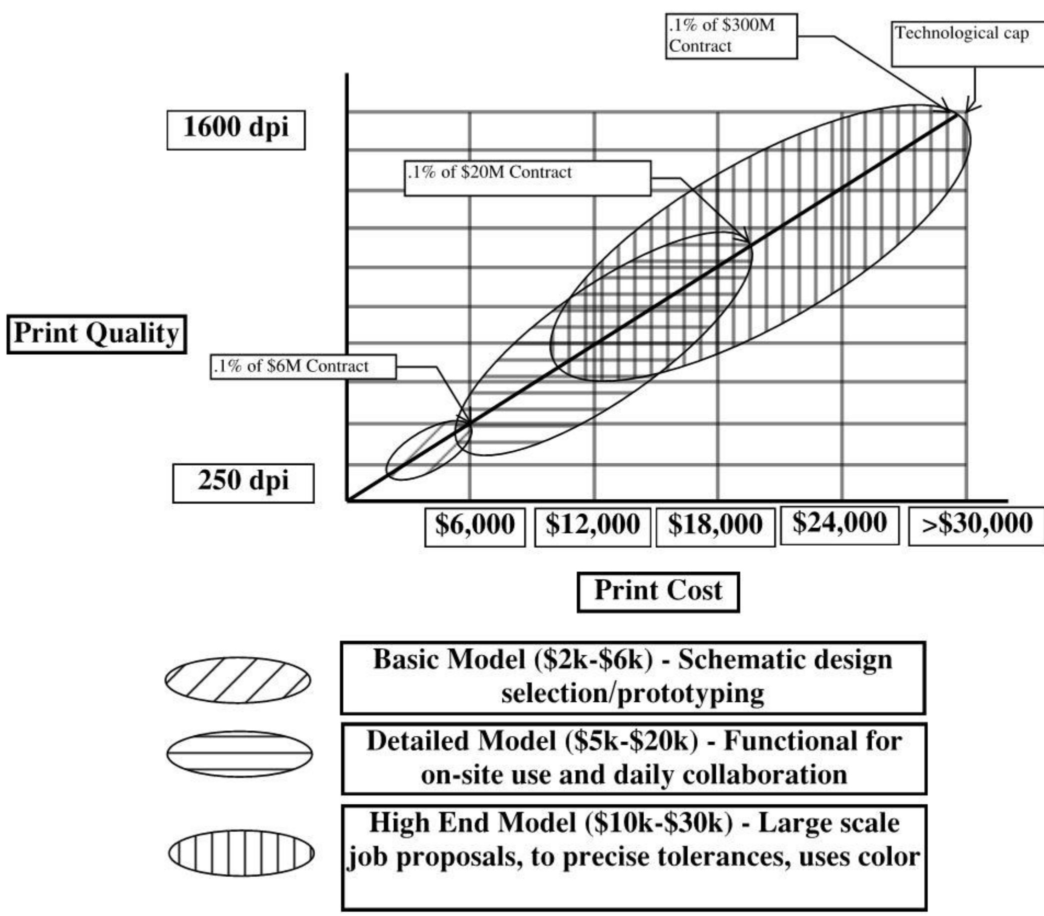
Cost Analysis

The larger the project, the more likely a model will be made for some reason. Models are typically created to impress an owner, communicate design to the public, or for analysis such as shade or wind studies. Since these are deemed as necessary, the cost to create these models is not constrained by the total cost of the project. 3D printing is already driving down the cost to perform all of these objectives. This makes it more viable, especially for a project that is questioning the requirement of a 3D model. A contractor can benefit from the models as previously stated, but at what cost? "An outsourced prototype can cost from several hundred dollars for a simple design to thousands of dollars for a more complex model – as much as three to five times that of a part printed in-house. Creating the same prototype on an in-house 3D printer brings a significant cost saving, even if your company prints only two models per month on average. These savings are augmented by designers and developers not having to wait for prototypes to return, time to market savings, and savings on reduced manufacturing errors due to the ability to print many prototypes…" (Stratasys, ND).

Through a series of meetings with industry professionals who work for a large-scale contractor in San Francisco, a conservative estimate was established for the cost of the model as it correlates with the size of the project. The cost of a typical 3D print model equal to .1% of total project cost was agreed upon to be a reasonable and doable expense. This is merely a starting point for determining the cost of a 3D print based on economies of scale as it relates to the project size. This is a baseline cost that is reasonable for a $2 million to $300 million project budget using the standard costs of a 3D print today. Currently, as the methods and costs improve in the 3D printing industry, it is likely that the cost can be posted against the general overhead budget of the contractor or architect. The model would be intended for use internally by the project team. Once the owners discovers how useful the model can be to them, the requirement to provide a 3D model could start being included in the RFP (Request For Proposal) or project specifications.

There are numerous variables that go into the final cost of the model. “This is no longer a one-size-fits-all technology. 3D printers are available in multiple sizes. Because they are being customized for different work settings, the level of resolution varies as well. All of these factors mean that small businesses can shop around and find affordable equipment specifically suited for their needs” (Erickson, 2014).The economies of scale for a 3D print are largely based on the overall budget of each individual project and the purpose for the model. The cost and use are somewhat correlated since a smaller $20 million project typically will not have the same expectations of a model as a $300 million project. Figure 2 represents the correlation of a 3D print’s quality to cost, and categories for what purpose it will be used for. Perspective is given for how this cost affects a budget by showing the high end of each category based on .1% of the contract amount. The chart does not factor in start-up costs, cost of the printer or materials, licensing/software costs, or labor to build the model.

Figure 2 - 3D Print Quality to Contract Budget



The ability to predict the cost impacts are hindered by the lack of studies on 3D printing. "With a new set of technologies, one major question that manufacturers face is whether additive manufacturing will save time or money. But businesses lack a set of decision support cost models that can assess the cost benefits associated with additive manufacturing" (Elwany, 2014). Models that address particular details or individual spaces require a separate coordination and planning effort since it goes into more detail than depicting the project as a whole. The cost of multiple models for any range of uses could vary substantially once indirect costs of time, labor, and materials are considered.

Conclusion

The opportunities for a GC to utilize 3D printing are growing every day. While the technology to print a fully operational building is still in its infancy, there are desktop sized models that can be created today that have the capability to provide many benefits. The ability to harness the power of 3D printing relies on the training and experience of the personnel responsible for creating these models. All aspects of a GC's business, from job proposals for new jobs to site logistics, can be improved by using 3D prints. It is the decision of the GC of how much to invest in integrating this tool into the everyday operations of the company. What is certain is that all general contractors will have to continue to adapt to emerging technologies to remain competitive in the construction industry.

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