Case Study: Analyzing the benefits of using 3D printing on the Mexican Museum renovation project in San Francisco, California

Benjamin Jodis
California Polytechnic State University
San Luis Obispo, California

The use of three-dimensional (3D) printing is not yet prevalent throughout the construction industry. Although there have been some uses, each has been small and relatively experimental, however, a current renovation project to the Mexican Museum in downtown San Francisco utilized 3D printing to aid in design coordination. The decision came after the General Contractor, Webcor Builders, noticed a possible constraint in pouring a section of the foundation; a pair of nine-foot vertical concrete walls surrounding the elevator shaft. The walls posed a serious threat to the schedule and budget of the project, raising concerns with shoring, waterproofing, and constructability. This paper will look at how the use of 3D printing on the project aided in the design process; what issues gave way to the use of 3D printing; what benefits the physical 3D model added; and what some possible expansions on this technology could be. The decision to utilize a 3D printed model is not standard procedure when faced with design constraints. However, the implementation of the 3D model proved to be beneficial on multiple fronts and opened the door to more innovation surrounding 3D printing within the construction industry.

Key Words: 3D printing, Webcor, Mexican Museum, Foundation

Introduction

As technology rapidly advances, many industries are being completely re-envisioned. One advancement which gained quick notoriety was the Three-Dimensional Printer. This device allowed ideas and drawings to become reality with the click of a button. Early 3D printers took hours, even days, processing and rendering simple structures, such as a hammer or children's toy. Now, thirty years later, 3D printers have the capability to take a highly detailed and complex virtual rendering and produce a physical model of that same virtual drawing, with pinpoint accuracy in regards to scale, angles, and detail. Despite the groundbreaking optimization in moving from intellectual concept to physical creation, there are only a few industries utilizing this technology on a grand scale.

Currently, there is no widely known use for 3D printing within the construction industry. This could be in part to the resistance to change in processes amongst the management level employees, the lack of need for temporary fixtures on jobsites, or the tight budget-tight schedule nature inhibiting experimentation. The construction industry has always been one of, if not the, slowest industries in regards to procedural and technological advancement. Many believe the age gap within the industry has lead to the bottle neck in advancement. Others believe the nature of a construction budget and schedule are not conducive to attempting new methods. In order to find newer, better ways of doing something, there must be experimentation, trial and error. Unfortunately, trial and error really boils down to dollars and cents, and with average profit margins for a general contractor around three to five percent, spending money without guarantee of a profitable return is not something most construction managers choose to do. Additionally, the concept of putting money into a product that will not be a permanent feature on the job leaves little reason for contractors to experiment with 3D printing.

3D Printing on a Commercial Scale

The growth rate of 3D printing on a commercial scale is reaching exponential levels. Corporations from every industry and turning to 3D printing to optimize production and cut down costs. In 2005, there were only eighty patents regarding 3D printing technology, materials, processes, and software. By 2013 there were over six-hundred non-duplicate patents pending (D'Aveni, 2015). This number continues to grow as companies get creative with 3D printing. Many industries have looked to 3D printing to produce small parts for larger machines, since the product serves only a minor function and is on limited supply from a distant manufacturer. The less time spent shipping products means higher production rates and higher profit margins. The technology also serves to optimize assembly line style manufacturing. Traditionally, a product with multiple pieces would need to be manufactured separately and assembled later. Now, with 3D printing, one machine can produce the entire system in a fraction of the time. This has many companies considering upgrading to commercial grade 3D printers in lieu of traditional manufacturing equipment. The numbers surrounding this don't lie either, in 2014 the sales of commercial grade 3D printers were nearly one-third the total sales of industrial automation and robotics equipment (D'Aveni, 2015).

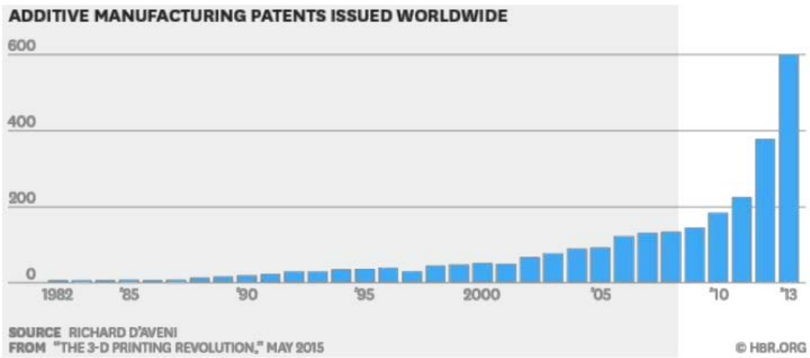


Figure 1: Growth rate of 3D printing patents

Construction Budget and Schedule

On average, the general contractor on a commercial construction project will take away anywhere from three to five percent profit on the job. The current budget for the Mexican Museum project is $500 million, meaning the general contractor, Webcor Builders, stands to make anywhere from $15 million to $25 million if all goes as planned. However, those numbers can start dropping rapidly if the project begins to hit a rough patch. Through liquidated damages, back charges, and decrease in production, a general contractor can quickly begin eating into their profit margin. A survey of seventy-six different construction projects indicated that seventy percent of the projects ran longer than the contractual schedule allowed for (Assaf & Al-Hejji, 2006). Additionally, of the top ten reasons contractors listed as cause for delay, owner change orders, the design team, and slow processing of documents appeared in seven out of ten (Assaf & Al-Hejji, 2006). Considering that delays are one of the biggest reasons contractors lose money on projects, it is important to find any way possible to minimize the possibility of delay. Furthermore, the main causes for delay include many issues that could be eliminated or minimized by implementing more efficient processes.

Methodology

The aim of this case study was to analyze how the utilization of a 3D printed model benefitted the overall cost and schedule of the Mexican Museum project. In order to do this, qualitative research was conducted through several interviews with industry professionals closely related to this project. Initial interviews were conducted with an individual directly responsible for the implementation of this 3D model on the project. Through these, a base of knowledge was formed regarding these main points:

- What was the initial design constraint
- How was the decision made to utilize a 3D printed model
- What was the product delivery cycle for the 3D model
- How has the 3D model aided the overall construction process

Several other interviews were conducted with industry professionals who were not immediately connected to this specific project but are involved in projects of similar scope and magnitude. The basis of these interviews was as follows:

- What potential is there for 3D printing within construction
- What is the biggest drawback to utilizing 3D printing
- How could 3D printing adapt to be more widely used throughout the industry

Case Study

The construction project in reference is a renovation of the Mexican Museum in San Francisco, California. Originally constructed in 1975, the main building of the museum will undergo a massive transformation, including seismic retrofitting, improved safety measures, and an aesthetic overhaul. Additionally, a forty-five-story mixed-use residential tower will be erected adjacent the existing museum. When designing the foundation for the new tower, it was discovered that a pair of nine-foot vertical walls would be needed around the base of the elevator shaft (Figure 2). Due to the condition of the soil, the depth of excavation required, and basic geometry of the wall, both nine-foot verticals posed a major constructability dilemma. After several weeks of unsuccessful coordination meetings, the decision was made to 3D print the base of slab excavation in efforts to alleviate some communication and design hurdles the contractor was anticipating.

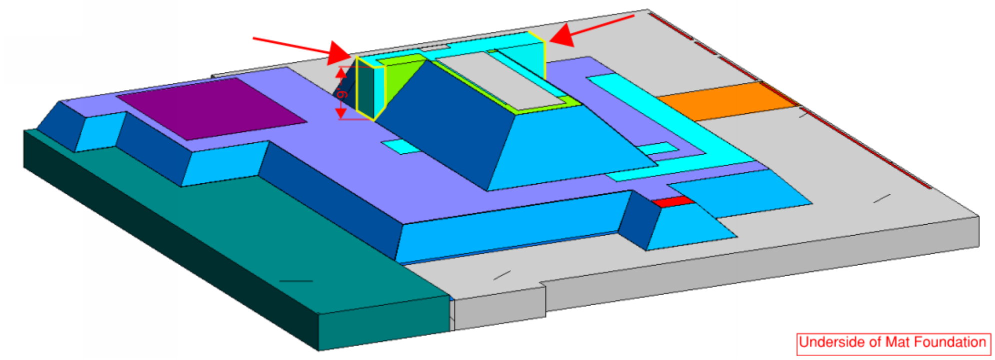


Figure 2: BIM model highlighting the nine-foot vertical walls in question

Project Details

Below is a list of the specific project details:

- Project Cost: $500 million (rough)
- Completion Date: June 2020
- Contractors Involved:
    1. Webcor Builders (General Contractor)
    2. Malcom-Silverado Joint Venture (Demolition and Excavation)
    3. Webcor Concrete (Structural and Site Concrete)
    4. Alcal (Waterproofing)
- 3D Model Details:
    1. Cost: $1,000
    2. Size: 12.75” x 12.33” x 2”
    3. Material: Versatile Plastic
    4. Manufacturer: Shapeways
    5. Lead Time: Two Weeks

Design Constraints

There were several constraints that arose from the requirement for the nine-foot verticals in the base foundation slab. These constraints are listed below:

- Excavating for a vertical wall of that scale
- Shoring the excavated wall

- Waterproofing around the sharp corners

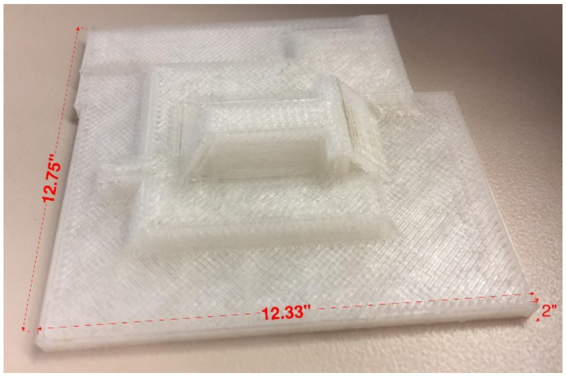
Excavation, Shoring, and Reinforcement

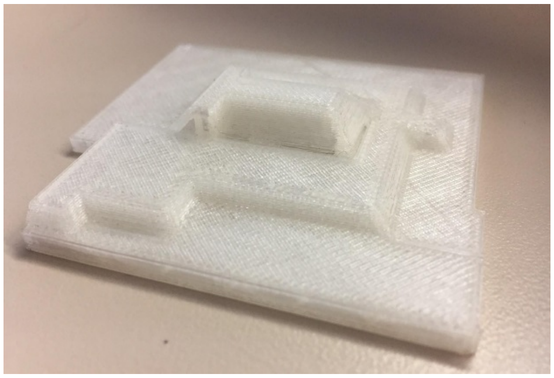
The largest issue surrounding this specific section of the foundation slab was getting to the point where the slab wall could actually be poured. In order to do so, the existing soil would need to be excavated, shored back, and formwork and reinforcement installed. Due to the height of the walls and their verticality, excavating the soil would need to be done very carefully, as the dead load above could very easily cause the soil to collapse. Typically, a foundation requiring this amount of elevation change would be done utilizing benching, a more gradual change in elevation utilizing sloped planes to gain elevation, not vertical walls. Once the excavation issue had been addressed, the contractor needed to develop a plan to shore, reinforce, the now excavated soil, in order to install formwork so the concrete wall could be poured. All of these issues tied into each other, so in order to solve one, the team needed to solve them all.

Initially, this issue was brought forth by the concrete subcontractor, Webcor Concrete, to the general contractor months prior to when it would begin to delay the schedule. Once the general contractor was made aware of the issue, multiple coordination attempts were made between all parties involved; the concrete subcontractor and their design team, the structural engineer, the soils engineer, and the owner’s representative. In doing this, it became apparent that the majority of the parties involved were still unclear on certain details. The design teams utilized 3D BIM models to assist with visualization and communication of the issue, however, multiple different team members still had issues visualizing their scope of work, thus dragging out the design process.

Implementation of the 3D Printed Model

Chris Kiteas, a Project Engineer for Webcor Builders, was responsible for the concrete scope of the project and the direct correspondent with the design teams during these coordination efforts. He noticed that the biggest thing people were still getting caught up on was simply being able to clearly visualize the model. During a monthly staff meeting, Chris proposed the idea of having the base foundation slab 3D printed to aid in the design and coordination of this slab, and shortly after he began researching companies capable of printing something like this in a timely manner.





Figures 3 and 4: 3D printed model of the base of slab excavation used on the project

Benefits as a Result

Once the physical model arrived at the job site, the design teams involved began holding on-site coordination meetings. After just the first meeting, all remaining concerns visualizing the problem were eliminated. The model became a way for each party to have a hands-on method of describing their own constraints as well as visualizing their proposed solution. While the team was discussing how to excavate, a member of the Malcom-Silverado JV team used tissues to represent the existing soil and removed them in phases to depict how he would best approach the problem. In only a few weeks, the majority of the coordination regarding the excavating, shoring, and reinforcement was resolved, an issue that had sat unresolved prior to the addition of the 3D printed model.

Another potential clash the contractor faced came as a result of the sharp ninety-degree angles formed by the nine-foot vertical walls. A foundation slab such as this one must receive proper waterproofing layers in order to keep moisture from the soil out of the building. However, the waterproofing layers that are required, are not designed to wrap around sharp angles such as that and ran a high risk of tearing at those corners. Fortunately, the responsible subcontractor, Alcal, was able to test out several real materials and proposed solutions on the model. Ultimately, the timely field tests of the materials on the model lead to slight design change that would eliminate the issue all together. This solution came after only a few coordination meetings on site, otherwise, a lengthy back-and-forth between Alcal, their retailer, and the designer would have been needed, involving numerous propositions and tests, only to establish the fact that proposed solution will not work.

The ability for designers to make quick mock-ups of their proposed solutions to test and then refine, all within a single meeting cut out a lot of time waiting on email responses from one party or another. The presence of the physical model during these coordination meetings drastically improved the productivity of the design team and allowed them to reach a resolution much faster than this problem would have likely taken had the initial approaches stayed constant.

Results and Discussion

Although the use of 3D printing is not common on construction job sites, it does provide several benefits when it comes to coordination amongst design parties. Being that construction is a relatively hands-on career, many people in the industry tend to be visual learners. The use of 3D modeling software has provided a major leap forward when it comes to communicating conceptual drawings, however, many still struggle with gaining a well-rounded understanding of the entire project or task. All of the industry professionals interviewed agreed that there is no substitute for seeing a problem first hand, in the field. However, when the issue at hand is something that physically cannot be seen in the field, such as a foundation slab that hasn’t been excavated for yet, the best option currently available are the various 3D modeling software. For this reason, the decision to have the foundation slab in question 3D printed was made, and suddenly, there was now a substitute for seeing something in the field, that was still more interactive and user friendly than a virtual model. The implementation of this model acted as a catalyst for the design coordination that was needed to overcome the challenge of the vertical section of the foundation. It created fluidity in meetings and bridged the gap between the design team and the experienced field superintendents, allowing both sides to effectively communicate in a manner both parties could understand.

Proposed Solutions

It only took a few weeks of coordination meetings once the physical model arrived for viable solutions to be agreed upon. After analyzing the model and discussing with the structural engineer, it was determined that the nine-foot vertical walls were not able to be changed in any form that would alleviate some possible excavation concerns, as the walls supported a large downward force caused by the elevator shaft they surround. One major concern that was especially prevalent while building in San Francisco was the combination of an extremely high-water table and unstable soil. During coordination meetings, it was determined that structural piles could be driven into the earth at the perimeter of the wall with sheet piles spanning the length between the corner piles (Figure 5). The site would receive a rough excavation to get down to the top elevation of the walls, then the piles were driven in and the exterior was excavated further down to the bottom of slab elevation. Once the piles had been exposed by the excavation, they were utilized as the back portion of the formwork for the vertical concrete walls. The solution was formulated by the civil engineer using the 3D model to communicate the entire process to the team.

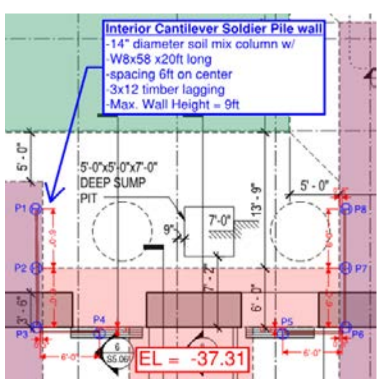


Figure 5: Drawings detailing shoring plan including layout of soldier piles and lagging

Once the excavation and shoring plan had been established, the issue surrounding the water proofing detail at the sharp corners became a pressing matter. In order to determine what the possible options were as far as a solution went, the team needed to see if there were any quick fixes that might solve the problem. Multiple types of water proofing materials were brought into the coordination meetings and placed on the corners of the vertical walls of the model and stress tested. Essentially, the subcontractor would pull the edges of the water proofing material tight around the right-angle corner and apply various pressure and forces to the material, specifically imitating shear forces the material might experience during earthquakes or shifting of the earth. It was determined that any sort of friction on the material at those corners would eventually cause the waterproof seal to be compromised. The team also looked at possible protection methods they could add to the material at the corners but were unable to achieve the moisture resistance rating required. The team realized the issue would not be fixed by the material because it was not the waterproofing material that was causing the issue, it was the sharp edges of the vertical walls. To combat this, it was proposed that the corners be chamfered to provide a rounded finish, allowing for a more cohesive coverage of the waterproofing materials. Fortunately, the solution was agreed upon prior to the walls being poured and a relatively simple feature could be added to the formwork to provide the rounded corner necessary. Both key issues that were addressed early in the design phase were able to be efficiently resolved through the use of the model, something Chris says would have taken a lot longer had they only had the BIM model to coordinate through.

Concerns Surrounding the Model

The decision to commission a 3D printed model in order to alleviate some design troubles was not an automatic one. Like most construction projects of this magnitude, the contractor is operating on a tight budget and a schedule with little room for delay. Having a 3D model printed would mean the contractor was spending money on a feature that isn't typically a necessary element for the team to effectively do their job. In addition, any time spent attempting to acquire this model is time that could have been spent actively trying to solve the issues. Both of these reasons usually contribute to the lack of exploration into alternative means and methods.

Another concern with acquiring the model was simply the model itself. Although the model would aid in the design process, it really played zero role as a permanent feature on the product. Traditionally, the majority of the material used during the design process is stored virtually and can be filed away in a hard drive for the owner once the project is complete. This model on the other hand, represented a physical product that would seemingly take up space around the office once it no longer served a purpose towards coordination efforts. Despite the concerns surrounding the commissioning of the 3D model, the contractor felt the risk was worth the reward; any money and time spent acquiring the model would be worth simplifying and expediting a conflict that might lead to delays and added costs if not dealt with ahead of time.

Conclusions and Future Research

Through interviews with two employees working for Webcor Builders on this project, it is apparent that the implementation of this 3D model was vital in avoiding a much bigger setback in the design process. Although the model only served a small portion of the overall finished structure, the idea of utilizing a physical representation, as opposed to solely relying on virtual renderings, opens the door to possibilities of further utilization of this technology.

Additional Uses

Currently, the method in which the 3D printed model was utilized could be easily duplicated for other elements of the building. For example, since the project includes the development of a forty-five-story building which will consist primarily of residential units, several floor plans could be modeled and printed to serve as a better visual representation of what the finished product will look like. Additionally, any major feature of the building's design that is causing coordination issues could theoretically be 3D printed in attempts to resolve confusion between the various parties.

Requests for Information

Expanding off this idea, there are several areas of the construction process that could use some optimization. For example, any change to the original design of the building must first be formally approved via the Request for Information (RFI) process. This involves formal written documentation outlining the change which is then sent through a lengthy review process on behalf of the designers and engineers impacted by the change. This process can take several weeks, and when work can no longer proceed until this change is agreed upon and improved, money is lost.

Submittals

A similar process ensues for the approval of all materials and products being installed on the job. This covers everything from paint to air conditioning units. Each product must first be approved through a formal submittal process, similar to the RFI process, where the product data is the item being review rather than a design change request. Both of these processes are extremely important to the successful delivery of the finished building, however, they can be time consuming. There are multiple scenarios in which, if approved, the use of a 3D printed mock-up could serve to act as a placeholder for the permanent feature while it goes through this phase. For example, if the architect is waiting on a mock-up from the manufacturer prior to approving that products submittal, a 3D printed version of that mock-up could allow for partial approval in regards to size, functionality, and aesthetic, while the architect waits on the official mock-up to approve material specifications. On any large scale construction projects, there are going to be instances when work cannot progress simply because one team member is waiting on a product to ship prior to the continuation of work. The use of a 3D printed model as a place holder, and even submittal reference, would allow work to continue without delay, ultimately saving the contractor money in the end.

Possible Evolution of 3D Printing in Construction

In the future, 3D printing could serve to act as a replacement for more raw materials used as permanent features on construction projects. This would require advancement of the material used in 3D printing, making it stronger, more economical, and more versatile. Below are several possible avenues 3D printing could take in the future of the industry:

- Custom tool manufacturing
- Replacement to traditional architectural features
- Official mock-ups for approval
- Alternative to costly temporary structures
- Wider use of concrete as a material for 3D printing

In order to fully benefit from 3D printing as a tool within the construction industry, the cost to print needs to come down, and the options for printable material type need to expand. If technology can advance to the point where it is comparable in price to 3D print a material such as concrete, as opposed to traditional pouring methods, a single 3D printer could take the place of dozens of laborers that are needed to spread and level the concrete as it is poured. Additional material options would allow for countless more uses of the technology, possibly making it become a much more realistic tool within the construction industry further down the road.

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