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# Evaluating Viable Additive Manufacturing Alternatives In Comparison to Traditional Construction Methods

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Additive manufacturing, also known as three-dimensional printing (3DP), is a technique of producing desired objects from feedstock, typically filament, input. This process currently has several applications in construction, some with potential for large-scale implementation in industry. Five applications, or alternatives, were considered and compared based on their equipment costs, unit production savings, scalability, output time, and operational crew size. Three alternatives showed the most potential value for implementation into industry. Viable alternatives include 3DP walls, 3DP small offices, and 3DP concrete roof tiles. These viable alternatives were further explained with benefits and impediments that could affect real-world production. Entities that would consider implementing 3DP as a construction method would join other innovative companies at the forefront of utilizing new construction techniques.

**Key Words:** Additive Manufacturing, Concrete Homes, Concrete Roof Tiles, Three-Dimensional Printing, 3DP

## Introduction to Three-Dimensional Printing

Three-dimensional printing (3DP) ranges from common tabletop (thirteen inches wide by thirteen inches deep by fifteen inches tall) machines that extrude thousands of layers of plastic filament into replicas of engineered assemblies to 10 feet tall machines that use a six-axis arm and metal alloy filament to produce unbroken cross-braced designs with an emphasis on structural integrity (Relativity, 2021). The construction industry uses 3DP as an automated way to develop architectural models, replacing hand-made methods. Research into development of physical 3D models, using 3D computer modeling programs such as Revit, shows that clients prefer to see a rendering rather than a set of plans (Wu, Wang, & Wang, 2016). However, the application of 3DP can also be used for producing structural components. While there were many startups in this area, one firm has shown the most successful to date, ICON.

ICON is a residential and space entrepreneur company based in Texas that has been using the emerging technology to produce the first 3D printed homes for sale in the United States (Nellemann, 2018). A goal of Icon was to develop a large-scale 3D printer capable of using concrete-like filament to create family sized long term livable homes (Projects, 2021). To achieve this goal, ICON has developed a proprietary concrete-like filament called “Lavacrete”. This material is used on exterior walls and some interior walls, providing load bearing structural support, as well as achieving desired R-values by being used in conjunction with a batt insulation system (Projects, 2021). The use of the Lavacrete walls allows for less traditional wood framing to be used, reducing outsourced materials used in the construction of the structure. Traditional activity lead times are reduced by printing the walls on site, allowing for a shorter delivery time of the overall project.

International companies such as Winsun, use 3DP for a variety of purposes related to the construction industry. They make 3D printed structural precast beams, 3D printed precast panels, and 3D printed portable multi-use spaces to name a few. They produce 3D printed construction materials that are used globally, with customers in countries such as Nigeria, China, and France (3D Construction, 2019).

## Relevance to Construction

The purpose of this paper is to highlight capabilities of 3DP currently used in construction and evaluate emerging construction methods. The importance of 3DP in residential construction is due to the production of the wall system in one to three days, instead of one to three weeks using wood light framing. Also, homes can be designed to custom specs including curved walls, and traditional framing techniques are no longer the limiting factor in designs regarding load capacity. As the recent trend of working from home continues, Mighty Buildings has the advantage of using 3DP to produce “tiny houses”, that can function as small modular offices, at a faster rate than traditional methods (Pricing, 2021). Icon claims that a 500 square-foot home can be printed in 24 hours (Projects, 2021). Winsun claims an 1100 square-meter, or 11,840 square-foot, house can be printed in three days (3D Construction, 2019). As supply chain issues are prevalent to the steel industry, the commercial construction industry receives delays. 3DP technology can be used to manufacture lightweight beams to replace traditional precast or wide-flange members. Implementation of printed beams in commercial construction could reduce reliance on lead times from steel suppliers experiencing delays. Lead times for projects could be reduced with the development of printed roof tiles. Oshkosh Public Museum used 3DP to repair a section of terra cotta roof tiles in 2020 (Oshkosh, 2020). The execution of this repair was completed with clay filament, but cementitious material works in the same manner with the same machinery.

## Methodology

Data used to calculate traditional framing output was collected from a report generated by the National Association of Homebuilders for the U.S. Department of Housing and Urban Development (NAHB, 1994). Current framing cost data was collected from estimate suggestions available on Home Advisor (O’Keefe, 2021). Beams were chosen to be wide-flange “W” steel beams and multiple sources were considered. A sample of beam prices gathered from MK Metal (Wide, 2021) was compared with prices listed in Texas (2020) and Indiana (2011). The average cost was $1.05 per pound of steel for all comparison calculations. Prefabricated small office data was considered from Home Guide, included in a report for square-foot estimates for modular homes and home additions (2021 modular, 2021). Bus stop manufacturing cost was gathered from Twin Modular Services at a price of $7800 for a size of 8’ x 15’ footprint unit (8 x 15, 2021). Manufacturing time was considered to be one day, since the factory can produce several units during a workday. Factory produced concrete roof tiles were considered from Boral Roofing (Boral, 2012). Tile dimensions and weights used for calculation were gathered from the Boral Villa product information (Boral, n.d.). Production cost data was collected from "Concrete Tile Roof Cost in 2021: Boral & Eagle Roofing Tiles" available on the Roofing Calculator website (Boesky, 2021).

## *Alternatives and Requirements*

The modes of application, also known as alternatives, of additive manufacturing to the North American construction industry reviewed are walls, beams, small office buildings, bus shelters, and roof tiles. These alternatives were subjected to requirements outlined in Table 1. These requirements were used to determine the five alternatives to be evaluated from a number of other processes performed with 3DP. The first requirement was that the alternative had to have a comparable traditional construction method. The purpose of this review is to determine the best application of 3DP, not to propose new construction techniques. The alternatives had to be applicable to many construction types, meaning that proprietary processes were not included. The third requirement was that they have to use materials that are readily available. Machines requiring alloy forging processes to generate filament were not considered. Filaments used by printers in this review are Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and cementitious material known as *Sikacrete*. Each alternative had to show potential for the ability to be an improvement over a comparable traditional construction method. Alternatives that could not beat standard production cost, weight, output, or time were not considered. The last requirement is that alternatives had to meet minimum strength requirements commonly used in North America, such as IBC regulations for homes and offices, ASTM A36 for steel, ASTM C109 for hydrolyzed cement, and ASTM C1492 for concrete roof tiles.

Table 1

*Requirements Used to Choose Alternatives*

| Requirement | Name |
|---|---|
| 1 | Current comparable method in industry (Innovative approach vs. existing approach) |
| 2 | Generalizable to multiple construction types |
| 3 | Uses readily available materials (filament) |
| 4 | Shows a level of improvement/benefit over traditional method |
| 5 | Passes ASTM strength standards/codes |

## *Measures of Merit*

Five measures of merit were used to rank the mode alternatives, shown in Table 2. The cost of machinery measure consists of the total cost of purchasing one printing process machine, without shipping. The cost of machinery will be higher as the size of the machine needed increases. The percent savings measure relates the cost of production per unit compared to traditional construction methods, without overhead and indirect costs. The feasibility of scalability is a subjective measure based on current levels of use and potential for further development, with a score of 1 being low and 3 being high. The percent output measure compares the time of production per unit with traditional construction methods. Operational crew size is the amount of people needed to operate and monitor the equipment.

Table 2

*Measures Of Merit*

| Measure of Merit | Name | Is a high value good or bad? |
|---|---|---|
| 1 | Cost of Machinery | bad |
| 2 | Percent Savings vs Traditional (product) | good |
| 3 | Feasibility of scalability (subjective) | good |
| 4 | Percent Output vs Traditional | good |
| 5 | Operational Crew Size | bad |

## *Calculations*

Printer cost data was collected using the Aniwaa website (3D Printer, 2021). This site lists printer capabilities, specifications, and prices, separated into categories based on uses such as industrial, commercial, and desktop. Concrete printer data was considered from the guide for construction printers also published on the Aniwaa website (Ultimate, 2021). Output for 3DP walls was based on Icon's statement that a 1,000 square foot home could have walls printed in two days (Nelleman, 2018). Traditional wood framing production of one week was derived from two weeks to complete framing for a 2000 square foot home (NAHB, 1994). Printed walls are used currently by several companies in the United States and internationally, so Feasibility was scored as 3. Printed beams are being researched, but not used in industry yet, so they were scored 1. Printed small offices are being used in the United States, but are currently made by one company, Mighty Buildings. Winsun produces printed modular offices overseas, so a score of 2 was given.. Printed bus shelters were developed by Winsun to achieve a sustainable design goal but are not being produced by another company. This lack of interest earns the score of 1. Printed roof tiles were used by a museum in the United States and proven to be successful. Similar success has been achieved with researchers printing cementitious materials for coral reef repairs (3D Printed, 2021). The scalability of printed roof tiles scored 2 because it shows potential for more utilization. A printed beam would take one day to print. A rolled beam would take one day to produce, with steel material lead time and transportation not considered. A modular office would take one day to print. Framing would take two days. A bus stop would take one day to print, (as low as two hours), as claimed by Winsun (Global, 2021). A manufactured bus stop could be assembled in one day at a factory. Both options could produce several bus stops in one day. Several hundred roof tiles could be printed in one day, while allowing another day to dry (3D Printing, 2021). Concrete roof tiles from a factory would take three days to manufacture. Considering time to print roof tiles assumes dry mix is available on site and time to hydrate, mix, and feed the printer is optimal. Manufacturing time used for roof tiles only considers the process time at the production site, not ordering time. Crew size was determined based on data from direct knowledge of using printers and information available on the Aniwaa Additive Manufacturing website (3D Printer, 2021). Table 3 shows data calculated for each alternative and measures of merit.

Table 3

*Alternatives and Data Calculated*

| Alternative | Name | Cost of Machinery | % Savings vs Traditional | Feasibility of Scalability | % Output vs Traditional | Crew Size |
|---|---|---|---|---|---|---|
| 1 | 3DP Walls vs WLF | 100000 | 0.64 | 3 | 250 | 2 |
| 2 | 3DP Beam vs Rolled Wide Flange | 40000 | 0 | 1 | 100 | 1 |
| 3 | 3DP Small Office vs Spec | 35000 | 0.7 | 2 | 200 | 2 |
| 4 | 3DP Bus Shelter vs Covered Bus Stops | 30000 | 0 | 1 | 100 | 2 |
| 5 | 3DP Roof Tiles vs Concrete S Tiles | 10000 | 0.32 | 2 | 150 | 1 |
| Best Value Presented | | 10000 | 0.7 | 3 | 2.5 | 1 |

## *Weighting and Scoring*

The weight of categories was selected to emphasize start-up cost to purchase a printer and savings that printing offers compared to traditional construction, shown in Table 4. Feasibility of scalability was considered to be more valuable than output to allow for future implementation of large-scale production to be considered more than direct output of one machine. Output and operational crew sizes were considered as low weighted factors due to high importance when starting a business to develop techniques mentioned, but importance dropping towards negligible once a company grows and is capable of mass-production and operating with a staff of employees. Normalized score standardizes the best value in each measure of merit as 1 and relates the value from other alternatives as a percentage of the best value. Weighted score multiples the normalized score of each alternative in each measure of merit category by the assigned weight of the category. Total weighted score sums the five weighted scores for each alternative and produces a decimal number that allows the alternatives to be compared.

The total weighted scores of 3DP Beams and 3DP bus shelters are less than half the value of the other three alternatives due to them both having no perceivable cost savings compared to current methods. Beams made from PLA or ABS would be up to 80% lighter than traditional steel W Sections, as mentioned in Noe (2021), but material cost could not outweigh using steel. As steel W section was considered to be $1.05 per pound, a beam of 100 pounds would cost $105. A factor of 75% weight reduction was considered for PLA and ABS filament material, meaning that 25 pounds of filament would be considered. A bulk-sized, 25-kilogram spool of ABS was $490, meaning that 25 pounds of material would cost $222 (Push Plastics, 2021). A 25-kilogram spool of PLA was $450, calculating to $204 for 25 pounds of material (Push Plastic, 2021). Both of these costs are greater than the list price for a steel beam, not considering shipping and transportation factors. A cost of filament material under $4.00 per pound would have shown cost savings compared to steel. The 3DP walls, 3DP small office, and 3DP roof tiles have similar values, all over 0.6 total weighted score. This means that all three alternatives have potential to be implemented into industry, with production scale not considered.

Table 4
*Decision Matrix*

| | Weight: | Score: | **3DP Walls vs WLF** | **3DP Beam vs Rolled Wide Flange** | **3DP Small Office vs Spec** | **3DP Bus Shelter vs Covered Bus Stops** | **3DP Roof Tiles vs Concrete 'S' Tiles** |
|---|---|---|---|---|---|---|---|
| Cost of Machinery | 0.3 | Normalized | 0.10 | 0.25 | 0.29 | 0.33 | 1.00 |
| | | Weighted | 0.03 | 0.08 | 0.09 | 0.10 | 0.30 |
| Percent Savings vs Traditional (product) | 0.3 | Normalized | 0.91 | 0.00 | 1.00 | 0.00 | 0.46 |
| | | Weighted | 0.27 | 0.00 | 0.30 | 0.00 | 0.14 |
| Feasibility of Scalability | 0.2 | Normalized | 1.00 | 0.33 | 0.67 | 0.33 | 0.67 |
| | | Weighted | 0.20 | 0.07 | 0.13 | 0.07 | 0.13 |
| Percent Output vs Traditional | 0.1 | Normalized | 1.00 | 0.40 | 0.80 | 0.40 | 0.60 |
| | | Weighted | 0.10 | 0.04 | 0.08 | 0.04 | 0.06 |
| Operational Crew Size | 0.1 | Normalized | 0.50 | 1.00 | 0.50 | 0.50 | 1.00 |
| | | Weighted | 0.05 | 0.10 | 0.05 | 0.05 | 0.10 |
| Sum (Weights) | 1 | Total Weighted Score | 0.65 | 0.28 | 0.65 | 0.26 | 0.73 |

## Results and Interpretations

The results of the decision matrix can be interpreted to show which application of additive manufacturing has the most potential for future use in industry. The highest rated alternative was 3DP roof tiles, with 3DP walls and 3DP small offices tied for second. The alternatives at the bottom of the ranking are 3DP beams and 3DP bus shelters. The option for lightweight beams to replace standard wide flange beams does not show potential based on the current prices of bulk printer filament compared to steel. Modular bus shelters are not a viable option either because they use too much filament, which current prices cannot overcome traditional costs to order from a supplier. The alternatives that show potential for use are 3DP walls, 3DP small offices, and 3DP roof tiles. The option for 3DP walls is not the highest rated option because of the barrier to entry. The machinery for this option is the most expensive, over double the price to purchase compared to the next highest option in the list. Based on the weight of the measures of merit, 3DP walls would be the best option to pursue if machinery costs were lower. The option for 3DP small offices has merit for potential industry use. The equipment cost is relatively low, matched with high savings compared to wood framing, and quick build time. The highest rated choice from the DMM is to print concrete roof tiles to replace ordering from local suppliers. This alternative has the lowest price of machinery and provides benefits in production cost savings and in output time when compared to ordering tiles from a factory through a supplier. The interpretations of results of the decision matrix regarding viable alternatives are included in Table 5.

Table 5

*Interpretation of Results from the Decision Matrix*

| | **Benefits of Development:** | **Obstacles to Development:** |
|---|---|---|
| 3DP Walls | ● High production cost savings<br>● High production output<br>● High scalability potential | ● High cost of entry<br>● Meeting local building codes |
| 3DP Small Offices | ● Low cost of entry<br>● Highest production cost savings<br>● Modular design<br>● High production output | ● Low current scalability<br>● Unknown market bubble |
| 3DP Roof Tiles | ● Lowest cost of entry<br>● Easiest production | ● Low current scalability<br>● Meeting testing standards |

## Conclusion

Viable additive manufacturing methods include 3DP walls, 3DP small offices, and 3DP concrete roof tiles. Pursuit of each of these alternatives has its own benefits and obstacles that should be considered. Implementing any of these viable techniques has potential to be more efficient than traditional construction methods. As additive manufacturing research grows in popularity within the construction industry, further improvements to the technology will take place.

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