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Exploratory Study of 3D Printed Homes: How It Disrupts the Residential Construction Industry

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Abstract: Innovations are difficult, from concept to implementation and customer acceptance, the ability for an organization to innovate, strains its resources. 3D printed products have begun to find its foothold in industries that use plastics and polymers as its main raw material source for production. Current 3D printing constructors organize their businesses with the future in mind, strengthening the development of the innovation and managing the vision of future clientele A 3D concrete printer can print a 1900 sq ft home in 48 hours over a course of 8 days reducing 20 separate tasks to 3 individuals and reducing construction time by 71%. The construction industry is responsible for 40% of global energy consumption and 40% of developed countries waste; a 3D concrete printer is fully electric and reduces fuel consumption by eliminating the need for generators and jobsite travelers. This paper offers an exploratory analysis of 3D Printed homes and explains how it can disrupt the residential construction industry. The findings of this study suggests that the innovation of 3D printed homes has the potential to provide a future for easily customizable options that can be used philanthropically to provide the global civilization, with protective shelters. Also, given that US home prices are growing faster than income and inflation and the material prices for conventional home construction continues to skyrocket, 3D printed homes have the potential to disrupt the conventional methods of homebuilding and attract buyers who are looking for more affordable housing.

Keywords: Disruptive Innovation, 3D Printing, Housing

1. Introduction

Disruptive innovations and inventions have been the accelerant to propel mankind into new eras for centuries. Disruptive innovations in the present era, are not always so easily recognized due to the exponential expansion of world digitalization. New technologies can create new markets and radically change or disrupt, the status quo in existing markets (Nagy et al., 2016). Some of the defining disruptive technologies and innovations that characterize the latest revolution are Mobile Internet, Artificial Intelligence, Robotics, Autonomous Vehicles, 3D Printing, Advanced Genomics and Renewable Energy to name a few.

Especially, Three-Dimensional (3D) printing is getting an exponentially increasing attention (Tay et al., 2017). Innovative 3D printers make forging, die-casting, lathe turning, drilling, broaching, brick laying (for building, construction) partially, or completely redundant (Majumdar et al., 2018). Despite all the recent developments, daily practice of using 3D printing is still in its infancy (Perkins & Skitmore, 2015). Many constructors follow the traditional ways of building and remain conservative to avoid the risk of losing profits. These constructors will be a challenge to convince changing their current building process. For some, rightly so, overcoming the technical, economic, and social challenges that need to unlock the opportunities from 3D printing in building sector, will be a complete overhaul in their current operation (De-Schutter et al., 2018).

The innovative idea of 3D printing in the residential construction business sector is in the early stages of taking a foothold in the construction industries. Many of these companies are new businesses with a wide variety of expertise and experience behind their operations. There are several claims as to why a 3D printed home should be enticing in the real estate market. It is intended in this paper to understand how a 3D residential construction is efficient, to provide feedback into how a 3D printed home reduces waste and discover how affordable a 3D printing is and could become.

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2. Background Information

Commercial and residential buildings have been designed and constructed in nearly the same way since the early 1900's (US Census Bureau, 2021). 3D printing was originally theorized by Murray Leinster in his short story "Things Pass" Then, in 1971, Johannes Gottwald submitted the patent for a Liquid Metal Recorder, patent number US3596285A. The patent defined that printing was the term to be used but it would not be solely used to describe the writing of characters with ink, but also any flowable substance. It was also stated that it was currently cost and size prohibitive to design a machine that was able to print with larger flowrates. Serious developments in 3D printing began in the 1980's beginning with Hideo Kodama's XYZ plotter that would place photosensitive resin and rapidly harden it with UV light. His experiments were published in late 1981. His process had a specific use, and it is more appropriate to call it "Rapid Prototyping" (US Census Bureau, 2021). Unfortunately, his research budget was very low, and his invention received little interest.

In July 1984, entrepreneur Bill Masters submitted a patent for his design, which he named Computer Automated Manufacturing Process and System. It was the first of 3 patents of his that gave rise to 3D printing systems that today's equipment still uses. The rest of the 1980's saw massive growth in the knowledge and design of printing methods. Startups such as Howtek were involved in the development of commercialized inkjet 2D printers that used melted plastic ink. The team worked to perfect the single nozzle hot-melt inkjet that used a solid plastic supply. In 1984 Chuck Hull developed the file format that most modern 3D printing systems use and coined the term "stereolithography", or SLA for short, as well as started his company called 3D Systems.

The technology for 3D printing continued to develop for plastics and other materials during the next two decades. In 2004, a professor at the University of Southern California, Professor Behrokh Khoshnevis, attempted the first 3D printed concrete wall. This is considered to be the first foray into the construction field for 3D concrete printing. Hwang and Khoshnevis (2004) wrote one of the first papers on 3D concrete printing titled "Concrete Wall Fabrication by Contour Crafting" in the same year. In the paper, they discussed the feasibility of Contour Crafting to produce full-scale concrete walls and detailed important characteristics such as speed, materials variety, and even the use of reinforcement in an automated setting. These important characteristics mirror those required of earlier developed 3D printing systems albeit at a much larger scale and for significantly different use. The scientific research they conducted paired with their undeniable success helped spark serious interest in 3D concrete printing.

As a result, there are multiple companies in the U.S. devoted to designing and producing printed concrete structures. In this paper we will discuss the innovation of 3D concrete printing and its potential to act as a disruptive technology in the residential and commercial construction field.

2.1 Recent 3D Printing in Construction

3D concrete printed homes offer a unique value proposition: have a new home in half the time for half the price. Multiple companies that specialize in 3D printed homes, such as SQ4D, say that they can print a home structure up to roughly 1900 sq. ft. in just 48 hours of printing time over the span of 8 days with their current ARCS printer (Kevin, 2021). Their ARCS printer can print 41% of the total construction of a home with as little as 3 people in that time frame, consolidating an estimated 20 separate manual labor tasks and reducing the total construction time by 71% (Kevin, 2021). According to the National Association of Home Builders with data presented from the Census Bureau, in 2019, 90% of homes were wood frame construction, roughly 10% were concrete, and less than 1% were steel frame. Over the past 10 years the concrete home sector has increased production by over 250% and its share of the market has doubled to 10% (Dietz, 2020). This can partially be attributed to building code changes in the South, specifically hurricane vulnerable regions. 3D printed concrete homes have the potential to drive that market share up even further for a number of reasons. Most notably, the global pandemic of 2019-2021 caused lumber shortages and since demand is still high, prices remain higher than double for standard building materials well into 2021 (Logan, 2021). Concrete availability also dropped, but the 3D printing technique uses substantially less material than a standard concrete construction, allowing for the price difference factor to remain the same between wood frame and 3D printed methods. The first 3D printed home was constructed during the materials shortage and is priced at half the region average (Kevin, 2021).

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Figure 1. First 3D Build House

Historically, performance in the American housing market meant the structure met the local building codes, had the desirable features of a home including extra space, garage, and a logical layout, and was priced to be competitive given the amenities available. During the pandemic, the nearly 28 million Americans that were already burdened by their current housing could benefit considering another performance measure that has become more important every year – affordability. SQ4D stated that their first house (Figure 1) was a success, and they will strive to continuously improve the quality of their process and reduce already low costs even lower (Kevin, 2021). Yet another historically important measure of performance in a home is the visual appeal of a home and associated property. The unique look of raw printed concrete may attract some but repel others, even at a lower cost point. As the 3D printed market continues to grow and the eyes of the general public shift from excitement at a new proven concept to opinions on visual appeal, we will probably see a separation between keeping the printed look and covering the concrete to appear with a more traditional exterior. The historical measures of performance here may not be affected at all regarding visual appeal as the raw printed look becomes adopted as a common sight in America. However, if companies like SQ4D and ICON can continue to build homes with an indistinguishable structure at a fraction of the cost, the current market may very well be permanently upset.

3. Operation of Innovation

Modern home construction projects have a multitude of operations that can quickly become delayed due to scheduling conflicts, undesirable weather conditions, and material procurement causing an increase in overall costs. A standard job sight must see the handiwork of builders, electricians, painters, plumbers, city inspectors, brick crews, insulation installers, etc. Many of these jobs can be delayed for days if not an entire season due to weather conditions. Roofing, for example, is just one place where properly timed work with favorable weather conditions must be considered in to minimize the risk of water damage to the interior structure. Moreover, rain and cold weather can compromise foundational work by restricting the growth of the crystalline structure of concrete. Finally, a multitude of material including drywall, bricks, siding, and wood for the housing frame work must be acquired and moved to the job site during specific project phases to keep the project moving as scheduled while minimizing overhead and possible material damage on site. However, each of these steps can be simplified with the use of 3D printed concrete for construction. A project utilizing 3D printed concrete can be operated with only 3 workers rather than multiple construction crews minimizing not only manpower but also the necessary logistical setup required for ascertaining and scheduling crews skilled at several technical trades. 3D printing consolidates more than 20 multi-labor intensive crafts such as siding, framing and sheathing (Kevin,2021). Current 3D printing concrete has been shown to be capable of a single day setup and is immediately able to start work. Completing the foundation and housing framework takes a matter of days instead of the average standard operating procedure that takes weeks. This capability minimizes risks associated with poor weather

conditions, significantly reduces the project timeline, and overall costs. Finally, 3D printing concrete allows for the use of a single material to do the work of many resulting in less work from payroll to supply chain.

3.1 Grounds for Efficiency

Currently, the construction industry has a great impact on the environment. The industry accounts for 40% of global energy consumption, 28% of the global greenhouse emissions, 12% of global potable water usage and generates 40% of developed countries solid waste. The use of a 3D printer for construction is fully electric. There would be no necessity for the use of generators or large number of workers needed on the jobsite to rely on fuel. Another waste reduction factor is that the accuracy of 3D printing results in less material waste. On most construction site, concrete pours use wood castings or frames, then dispose of the material after use. 3D printed construction doses do not require these moldings or formwork, alleviating unnecessary waste and producing a final project with what is necessary for the build (Perkins & Skitmore, 2015).

As an example of this innovation for efficiency, in January of 2020, a New York based construction company, SQ4D, completed a 1900 sq. ft. house using only 6000 US dollars of material. The company boasts that it was completed in 48 hours over an 8-day span. Using its robotic technology, it prints the foundations, exterior walls, interior walls, utility conduits and much more. There were only 3 people necessary during the robotic build (Kevin, 2021). With the increased speed of build times as well as the accuracy of building what is necessary and wanted, 3D housing is creating affordable products through efficiency and customization.

3.2 Business Model Innovation

Current home builders and construction companies have indistinct characteristics when attempting to identify the operations of their companies. These construction companies rely on their distinctive diversification of what they manufacture for the client. These companies promote a relationship of quality and loyalty to the vision of the client. Many of these companies do not dedicate business functions to create an intentional quality product for the client. The capabilities of the company's individuals play a more important role than creating distinctive business units within the company such as design, marketing, purchasing, material management or acquisition. A common factor that influences many of the decision-making within a firm is the customer. What makes it more challenging to operate the construction business, is coming together with the client to generate the concept that is envisioned and the changing of concepts of the client make creating the end product difficult for the project manager (Pekuri et al., 2013).

For a disruptive technology, such as three-dimensional residential home printing, there are ways to break away from the uncertain or loose business models of current home builders. The construction companies that have chosen to become an innovative business and provide the technology of 3D printed homes, can structure their business differently to address specific project management hurdles. The construction company with an innovation such as 3D printing of homes, should set up a supportive structure to align with the mission of the company. Complementary divisions within the organization will have a greater impact for propelling the innovation in the market, especially innovations where technology is the main driver for the business. The 3D printed home manufacturing business can deliver value to the customers by having dedicated teams to highlight individual expertise. These businesses can have specialized teams such as R&D, Production, Client and Culture, Engineering, and Sales. Allowing each team to focus on what they do well for the client will produce a quality product designed and desired by the client (Landry, 2020)

3.3 Current Provider and a New Innovation

Many of the construction companies in operation, operate their businesses within local markets. There is very little distinction among companies to diversify their operations, therefore limiting their growth. Larger companies can diversify by expanding geographically and/or expanding their knowledge into commercial or industrial construction markets. As previously stated, these builders lack a business model capable of supporting the addition of a disruptive innovation such as 3D printed houses. Incorporating an innovation into an established business is not ideal based on the ways that many companies operate their business which is basically project by project. In the organizations, there is not a perceived threat of a disruptive innovation, these companies compete among local benchmarks rather that continental or global markets. The standard business practices of residential home constructors will most likely not feel the necessity for new innovative opportunities until a disruptive innovation such as the 3D printed home has impacted their competition pool and effectively their ability compete for clientele. When a construction company begins to see reduced profits because of the 3D printing innovation, then they may begin to consider becoming more business minded for the organization and set longer future goals to keep up with a changing market rather that focus on their business project by project (Pekuri et al., 2013).

3.4 Future Development and Positive Implementations

The innovation of 3D construction is in its early development stages. Currently, 3D printed structures use combinations of cement, sand, silica fume and microfibers to strengthen and join the layers for construction. The future consumers may have demands for insulated or lightweight materials. It is perceived that the materials that will be developed for use of printed structures should continue to provide a high quality and low construction cost to continue to add value to their designs (Tay et al., 2017).

For now, the 3D printed innovation is being refined to provide a better more sustainable product for its clientele. A way to test and improve the construction process is simply to use it. There are a few notable examples of how companies are using the innovation to improve the circumstances of others. In Austin, Texas, a company, ICON, has taken its printer to a Northeast Austin neighborhood to print homes that could be used for the homeless and elderly. The company has planned a 51-acre development to include the construction of more than 500 homes for the cause. The company is using this project to, not only provide homes, but to refine the craft and showcase the printing units' capabilities (Jayson, 2020). ICON, has partnered with New Story Charity and Echale, to address the impoverished community of Tabasco, Mexico and combat those in desperate need of shelter. 3D printed construction homes, is an incredible step to revolutionize combatting global homelessness (Housing & Rover, 2021).

4. Discussion and Conclusion

When Murray Leinster first theorized 3D printing and wrote about it in his short story, he could only imagine the benefits the technology could provide in the future. Not unlike other inventors of the times, such as those who imagined flying cars or what endemic life was like on the moon, Leinster imagined a future where you could print anything and wrote science fiction novels to satisfy his passion for futuristic curiosity. The technology jump between WW1I and the 1970's was substantial and inventions such as the pacemaker, the radial tire, and the halogen light bulb were introduced. Civilization was even able to put a man on the moon before the first 3D printer was patented. Plastic manufacturing was progressing fast, and people could create just about anything out of plastic, even print. The first 3D printer was used to extrude ink that was an electrical conductor in any form of writing. It also used a material that was solid at room temperature but would be heated up and extruded for printing. This was the basic idea that would be developed for the next few decades with improvements on size, cost, and performance to create the well-known and commonplace Inkjet printer. In the 1980's development of printers began to diverge into ink style printers and ones capable of additive manufacturing with plastics. Further developments were made in coding, material feeding, and nozzle technology and in 2004 Professor Behrokh Khoshnevis created the first 3D printed concrete wall as a proof of concept aimed at breaking into the construction sector. The leap to true 3D integration in residential construction took another 17 years in the U.S., potentially because the housing market has been consistently growing since after the 2008 crash and lumber supply has not been problematic. The issue that has become quite apparent in the U.S is that the cost of housing has risen nearly twice as fast as inflation and wage growth causing millions of Americans to be burdened with their monthly housing costs alone. There could be many reasons why so many have such financial burden: being laid off, accepting a lower paying job, expecting higher pay in the future, or simply getting a larger mortgage that has a lower rate. One way to reduce financial burden is to simply get a lower payment and that may come at the cost of space, quality, or amenities in a typical housing selection. Companies like SQ4D and ICON have been testing their 3D printing products, ARCS and VULCAN, respectively, for years. SQ4D made a proof-of-concept house in January 2020 that took a mere 48 hours print time over 8 days with only 3 technicians and estimated 30% reduction in cost. The print cut out 41% of the total time to construct an occupancy-permitted home that was stronger, more weather resistant, and could last well over a century. Their next project has been claimed as the first 3D printed concrete home for sale in the U.S. The 1407 square foot home rests on Long Island in Suffolk County and has all the comforts of a home one could expect, including a garage. At $300,000 the sale price is significantly lower than the county average of $500,000 and half that of the region average of $610,000. If future home builds from similar companies can be as competitive at this in price, then the results of developing and utilizing 3D concrete printing technology can help substantially reduce the burden that nearly 28 million Americans currently face. It can also help prevent more from having to put themselves in a compromised financial situation just to claim they have achieved the "American Dream" of home ownership.

As with any emerging technology, there are limitations. The limitations of the study and utilization 3D printed concrete homes are many and these hurdles are the prime areas of investigation for entrepreneurs in the years to come. Currently in the U.S. at the time of this writing there is and only has ever been a single home for sale that has utilized 3D concrete printing to replace a significant amount of the total structure. There is also a proof-of-concept home that was built but will not be occupied. The technology creates designs that may not suit the visual tastes of some. Advances in the printer technology must also be made to create homes larger than one story high. Concrete has long been a staple of construction and measures must be taken to prevent cracking long-term. The main reason SQ4D was able to price the Long Island home so comparatively affordable

was because of the serious reduction in materials, labor, and waste. The potential to keep prices at a fraction compared to local markets will be reliant on supply of the unique blend of concrete. This may cause more rural projects to be at a reduced discount compared to their local markets, or even be unprofitable. One of the most problematic limitations of this analysis is the fact that of the hundreds of thousands of homes were built in 2020, only one of those was 3D concrete printed and that data represents a large part of the argument that this technology will one day actively disrupt the housing market for the better.

Overall, 3D printed homes have the potential to disrupt the conventional methods of homebuilding (Mohammad et al., 2020) and attract buyers who are looking for more affordable housing. SQ4D and ICON are getting national attention as 3D homebuilders that are leading the way for the development of this technology. 3D concrete printed homes will soon challenge the current housing contractor marketplace by creating an affordable homebuilding alternative.

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