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Adoption of 3D Printing Technology in the Residential Industry of the US: A Content Analysis

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In recent years, the US population of lower socioeconomic status has had an increased experience of uncertainty in being able to acquire affordable housing, and this issue is only being augmented by the limited innovation in the US residential construction industry. Although there is limited innovation being introduced in the US residential construction sector of the US, 3D printing (3DP) or additive manufacturing, a broader term utilized by industry professionals, has been at the forefront of discussion among Architects, Engineers, Constructors, Owners, and Operators (AECOO) in recent years. Utilizing a literature review, this study identified the 52 obstacles/barriers the construction industry faces in implementing 3D printing in the residential sector. Of the 52 identified barriers impeding 3DP adoption, the top three obstacles were Cost, Training Cost, and Complexity. The research also identified that most identified barriers could be associated with the Relative Advantage of the innovation. One of the practical implications of the study's findings is that there needs to be collaborative efforts between housing industry stakeholders, policymakers, and technology manufacturers to facilitate incentives and training programs to alleviate some of the obstacles/barriers identified in the research.

Keywords: 3D Printing, Home, Innovation Diffusion, Residential Construction, Obstacles/barriers

Introduction

There has been an increase in homelessness in the US in the last five years, and approximately half a million people experience homelessness (National Alliance to End Homelessness, 2023), with housing affordability contributing to homelessness. Across the US, affordable housing is becoming a concern due to numerous factors, such as lack of inventory, incomes not keeping pace with increases in home prices, a slowdown in housing construction, and others (Schaeffer, 2022). Although numerous housing technologies such as prefabrication, modular, and 3D Printing (3DP) exist, their use in solving the current housing affordability crisis is unknown. Further, even though 3DP technologies have successfully integrated themselves into various and distinct professional fields (Rogers et al., 2016), the construction industry is a difficult market to penetrate, with an astonishing rate of 40% to 90%, depending on the technology, fail rate despite the evident necessity for innovation (Sepasgozar & Davis, 2019). Previous studies define the current and foreseeable benefits of 3DP for AECOO professionals. However, there is insufficient literature on the comprehensive collection of barriers to adopting 3DP for residential construction.

Therefore, this research determined the obstacles/barriers to 3DP, especially given that it is an innovation for most stakeholders associated with the US housing industry. The research also mapped the 3DP obstacles/barriers onto the innovation attributes to determine which innovation attribute needs to be emphasized the most to facilitate successful adoption across the US housing market.

Background

Equitable housing opportunities for the vast US population have been a complex and arduous task from the very beginning of the creation of this nation (Woods et al., 2014). The common consensus among scholars is that housing affordability is defined as when a household spends less than one-third of its income on housing (Kang & Jeon, 2021). However, within the US, one-third of the households spent more than 30% of their income on housing, indicating a situation where housing is no longer affordable for that section of the population (Rose et al., 2023). The housing unaffordability impacts can be observed, with a significant part of the US population confronted with the possibility of eviction and over 150,000 Americans with children experiencing homelessness (Bovell-Ammon et al., 2021). Further, 7.1 million US households "*spent more than 50 percent of their income on housing*" (National Alliance to End Homelessness, 2023).

Between 2005-2009, the housing industry demonstrated a significant negative effect on home production due to the 2008 housing crisis, and although there was growth being experienced from 2015 to 2018, considerable progress needs to be made to match the current demand (Neal et al., 2020). Concurrently, the 30-year fixed-rate mortgages saw an all-time low, between 2020-2021, with rates decreasing to as low as 2.66% (Freddie Mac, 2023), but inversely, home price median were around $458,00 in 2022 (US Census Bureau, 2022), hindering low-income households from taking this opportunity. This pricing-out phenomenon demonstrates the necessity for affordable housing, and yet, the US construction industry has invested only 1.5% of its value into technology in comparison to the overall average in the economy of 3.6% (Hossain, et al. 2020) to incorporate the use of technologies to facilitate a housing paradigm that is affordable.

Alternative housing construction methods such as prefabrication, including modular and manufactured homes, 3D Printing (3DP), and others, are being employed to a certain degree to meet the demand in US residential construction. Modular and manufactured homes are produced in a factory, but a clear distinction between them is that modular abide by state building codes, while manufactured homes must follow federal building codes (Winter, 2001). Prefabricated homes offer a controlled work environment, quality control, energy efficiency, and lower cost that appeal to both the green movement and affordable housing solutions (Memari et al., 2014). 3D Printing (3DP) or additive manufacturing has the potential to alleviate some of the stresses imposed by external conditions, such as pandemics, the lack of labor, and others, in constructing houses economically and in a shorter duration. The technology or additive manufacturing consists of a filament, or building material, being deposited by a nozzle, or extended arm, controlled by a software system. With an extensive history of over four decades, 3DP's commercial success (Su & Al' Aref, 2018) expanded to various 3DP types throughout the years utilized in industries such as medical, automotive, aerospace, and others. 3DP methods have expanded and include:

1. Stereolithography: Using a laser to selectively target liquid resin from a tank position at the bottom of the 3D printer, hardening it into plastic (Jacobs, 1992).
2. Wire arc additive manufacturing: Metal wire is used as the material, and an electric arc is used as the energy source (Derekar, 2018).

3. D-shape: A binder jetting technology is used to selectively apply a liquid binder on top of layers of powder material consisting of a cement-sand blend (Jassmi et al., 2018).
4. Contour crafting: Presently being utilized for residential construction, the nozzle prints layer by layer (Fernandes & Feitosa, 2015).

One of the most prevalent issues is that 3DP, along with many other innovations in the residential industry, consists of updating building codes to allow for a new standard of construction (Koch, 2017). These codes are produced by the International Code Council (ICC, 2023) and are developed by professional organizations with expertise in their respective field, like the ANSI for construction. Coincidentally, the lack of research into the various aspects of 3DP, such as material testing, has hindered the progression of adoption among many who are still skeptical of its capabilities (Pan et al., 2021). Another consequential issue in the adoption of 3DP, proclaimed by various construction scholars, is the fragmentation of the construction industry and the necessary cooperation between fields of expertise (Luomaranta & Martinsuo, 2022). The interoperability of the multiple disciplines in the construction industry is crucial for the success of novel construction methods (Criminale & Langar, 2017). Through the content analysis process of 3DP, a limited quantity, along with a limited 15-year period, was observed, and further illustrates the necessity for further research of the multitude of innovations being procured to meet today's needs.

Given that the 3DP is an evolution, especially for the residential sector and its associated stakeholders, it can be considered an innovation. An innovation has been defined as "*nontrivial change and improvement in a process, product, or system*" (Slaughter, 1998). Depending on the adopting unit, this innovation can be sorted into product, process, or both (Langar, 2012; Slaughter, 1998). The need for innovation adoption for the residential industry, similar to 3DP, is highlighted by the fact that current residential industry materials and methods are vulnerable (Dong & Li, 2016) to ever-increasing (frequency and intensity) of natural disasters (NCDC-NCEI, 2019), environmental impact of the construction sector on energy consumption and CO_2 emissions to the atmosphere (IEA, 2019), and resistance of the industry to change. For innovation adoption, innovation attributes play a significant role (McCoy, 2008). Numerous innovation attributes play a role in its adoption and include Relative Advantage (RA), Observability (O), Complexity (Cx), Compatibility (Co), and Trialability (T) (McCoy, 2008; Rogers, 2003). Even though researchers have identified additional innovation attributes, these five were used for this research.

Thus, the research used a content analysis method to determine the 3DP obstacles/barriers for the AECOO industry. The content analysis was used as it provides an interpretative approach to the actions of entities and allows the compression of the significant quantity of textual data of a novel but broadly applicable 3DP technology into categories to represent the distinct facets of the text (Kandel, 2020).

Methodology

The research used qualitative content analysis to identify obstacles/barriers to the adoption and implementation of 3DP within US residential construction. An accessible and efficient content reduction technique, content analysis allows for a salient issue, with a significant quantity of textual data, to be compressed into categories representing the different facets within the text (Stemler, 2001). Further, the qualitative aspect of content analysis allowed for interpreting attributes or values, as stated in the text, for further insight as to why a specific situation is happening (Kandel, 2020). The first step in the research was the identification of search portals and keywords. The researchers used the Web of Science, and for diversification purposes, Google Scholar was also utilized. A particular combination of keywords was utilized on designated search engines. The keywords for search parameters included 3DP, home, residential construction, innovation diffusion, affordable housing, and USA. Approximately 730 documents were generated using keywords. All documents were then subjected to the following parameters: 1) Study applicability by review of abstracts; 2) Language (English). After the application of the parameters, the publication number was reduced to 49. Information relating to 49 articles was transcribed into Excel to determine the articles' demographics and the obstacles/barriers impacting the 3DP adoption and implementation. A table was created to determine the obstacle's intensity, and every time a publication identified the obstacle, it was mapped onto the table. For example, if an obstacle was identified in twenty-four publications, its strength was identified at 24. After identifying 52 obstacles/barriers with their obstacle strength, they were mapped onto the innovation attributes by the authors to determine which innovation attribute encompassed the most obstacles/barriers.

Results

Three identifiers were employed to identify this study's targeted demographic: article type, publication year, and application location. Most articles perceived 3DP and its related obstacles to be globally applicable (33/49), and when it comes to a particular country, the US (7/49) has invested the most resources in comprehending this issue, followed by China (Figure 1). Although the authors are affiliated with specific institutions and their respective countries, the researchers sought the value and improvement of 3DP globally. Further, the Chinese government has been an advocate of 3DP in residential construction for a prolonged period, relative to other countries, with their plans to build the largest 3D printed building group and have emphasized the criticalness of an international standard or set of building codes that are applicable to 3DP (Pan et al., 2021). When it comes to the US, the novelty of 3DP in the construction industry has garnered the attention of various professional entities, and in 2022, we are seeing significant progress with the construction of 100 3D printed homes consisting of 3 or 4 bedrooms, right outside one of the US most notable cities, Austin (Olick, 2022). Regarding article type (Figure 2), most publications were journals (39/49). In terms of the publication year, the initial publications can be traced to 2009, with significant interest increasing in the last few years.

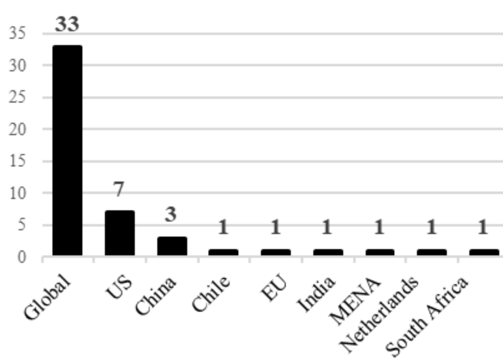


Figure 1: Application Location (n=49)

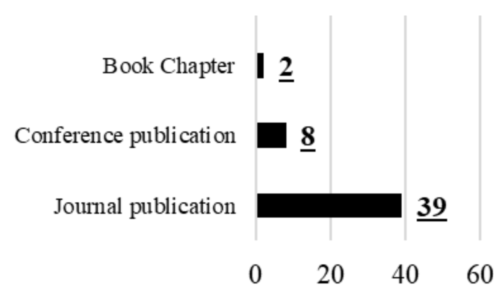


Figure 2: Article Type (n=49)

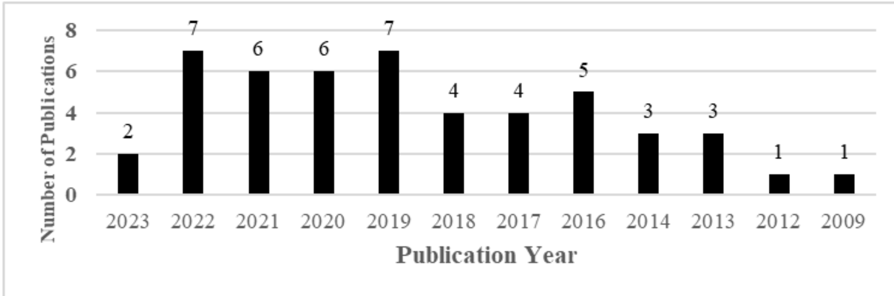


Figure 3: Publication Year (n=49)

Barriers to 3D Printing (3DP)

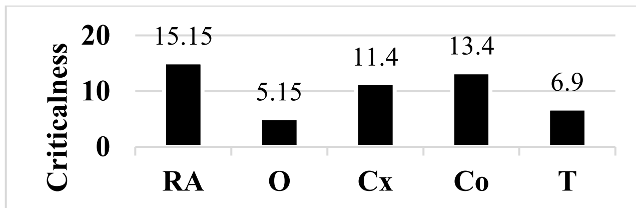
The research identified 52 obstacles/barriers based on the comprehensive literature review associated with 3DP adoption within the residential sector (Table 1). The top five obstacles/barriers (based on the frequency) included Cost (24), Training Cost (time and money) (21), Complexity (17), Limited Materials (17), and lack of standardization (17). Among the different technologies that have gained traction in the construction industry, Building Information Modeling (BIM) implementation barriers were somewhat similar to the ones identified in the research, with employee training and cost being the top two barriers (Criminale & Langar, 2017). Multiple researchers have identified cost as a significant barrier to adoption (Ullah et al., 2019). Although early adopters of BIM initiated in the early 2000's, giving BIM approximately two decades in the AECOO industries (Smith, 2014).

Table1: Barriers for adoption of 3D Printing (3DP) in the residential sector

Cost (24)	Training Cost (21)	Complexity (17)
Limited Materials (17)	Lack of Standardization (17)	Fragmentation of Industry (13)
Quality of Surfaces (12)	Lack of Federal Support (10)	Operational Structures (7)
Reduced Employment (5)	Method of Delivery (5)	Economic Vantage (4)
Intellectual Property (4)	Weather Dependent (4)	Social Acceptability (3)
Adhesion of Bead Layers (2)	Age (2)	Bead Layer Deformation (2)
Conservative Character (2)	Lack of Research (2)	Lack of Guidelines (2)
Lack of Proven Success (2)	Overhanging Parts (2)	Transportation of 3DP (2)
Anisotropic Behavior of Printable Objects (1)	Capabilities (1)	Carbon Emissions (1)
Chemical Degradability (1)	Data Interoperability (1)	Energy Consumption (1)
Energy Cost (1)	Environmental Hazard (1)	High Risk (1)
Housing Market (1)	Implement Assessment (1)	Interpersonal Relationships (1)
Lack of Data in Material Properties (1)	Lack of Multipurpose Technology (1)	Limited Availability of Automated Fabrication Technologies (1)
Limited Capacity for High-Rise Buildings (1)	Low Investment in Technology (1)	Low Level of Customization (1)
No "One Size Fits All" 3DP (1)	Nozzle Direction Changes on the Layer Density (1)	Observability (1)
Placement of Reinforcement (1)	Postprocessing (1)	Relative Advantage (1)
Supply Chain Disruption (1)	Uniqueness (1)	Usability (1)
Value of Property (1)		

Perceived Values

Relative Advantage (15.15/52) was perceived as the most consequential attribute in 3DP adoption in residential construction, encompassing the most barriers to its adoption, as depicted in Figure 4. Compatibility (Co), an innovation attribute, closely followed Relative Advantage (RA) in terms of the 3DP obstacles/barriers encompassed. Observability (O), on the other hand, encompassed the least barriers, indicating its importance in the 3DP adoption. Thus, using the findings, leveraging the RA and Co of 3DP can facilitate its adoption within the residential industry.



RA: Relative Advantage; O: Observability; Cx: Complexity; Co: Compatibility; T: Trialability

Figure 4: Mapping 3DP Obstacles to Innovation Attributes

Conclusion

This research identified 52 obstacles to 3DP adoption and implementation within the US residential industry using a comprehensive content analysis that included sources such as Web of Science and Google Scholar. The research found “cost” to be the most significant barrier to 3DP adoption in residential construction. The finding is crucial as most construction firms are small and comprise less than ten employees (Sacks et al., 2018), directly affecting what type of financial endeavors they can attempt without comprising their financial status. The finding is critical as previous research indicates that firm size is strongly related to innovation adoption (Langar & Pearce, 2014; Langar & Pearce, 2017). Due to a direct correlation between the size of the firms and revenue intake, the smaller firms will have limited capabilities to expand or upgrade their equipment. Another identifiable obstacle is the cost of training the workforce to operate the technology adequately, and this opportunity cost does not just engulf the monetary cost but also the time that could be spent on other projects (Memari et al., 2014). Again, this kind of financial venture can be viable for bigger firms due to the financial flexibility they can afford compared to smaller firms. This can be observed in another prevalent construction technology being implemented today. Although BIM offers clear benefits and frequent proven success, stakeholders are still hesitant to venture out and invest in newer technologies (Criminale & Langar, 2017). Furthermore, with the multitude of stakeholders involved, such as the general contractor, owner, architect, and subcontractors, to name a few, on a project, and that is subject to change per individual project, the need to coordinate and comprehend the complex information models that are implemented in 3DP or other similar unfamiliar technologies is crucial (Pinkse & Dommisse, 2009). Unfortunately, 3DP is a relatively new and complex technology, so the lack of information amongst AECOO professionals is a prevalent issue that cannot be overlooked regarding innovation adoption (Hossain et al., 2020).

Although novel innovations such as 3DP are necessary for the future success of the construction industry, Relative Advantage, the perceived distinction of innovation being an improvement in comparison to the superseded (Premkumar et al., 1994), is a significant predictor of adoption and, unfortunately, it was determined, through the evaluation and analysis of the textual data, that it was the main categorical obstacle (Besklubova et al., 2021). For one, the cost is deemed a Relative Advantage for 3DP, but this is regarding the reduction of production cost (Perkins & Skitmore, 2015), not the initial cost that many small construction firms won't be able to afford in their delicate financial state, as previously stated. Stakeholders need to perceive a technology to have a relative advantage over traditional methods, especially in a conservative industry like construction (Sepasgozar & Davis, 2019). General contractors, along with the other AECOO professionals, need systems that display efficiency in the various unique construction projects they are employed to do, and without the Relative Advantage initially assumed in 3DP, skepticism will only pervade.

One of the practical implications of the study's findings is that there needs to be collaborative efforts between housing industry stakeholders, policymakers, and technology manufacturers to facilitate incentives and training programs to alleviate some of the obstacles identified in the research. These proposed collaborative efforts can also help overcome the barriers associated with cost as the innovation (3DP) does not have substantial historical precedents in the US residential industry.

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