Key Barriers to the Adoption of 3D Printing Innovation in Construction: A Review of Empirical Studies

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Abstract
The need to implement sustainability in construction has given birth to 3D printing innovation. It is also a potential construction technique by which the construction industry contributes to sustainable development. 3D printing has recently gained more interest in construction, thereby promising automation of building processes with its advantages in faster production, cost reduction, material minimization, and greater environmental soundness. However, numerous barriers have limited the adoption of 3D printing in construction in various parts of the world. Little consideration has been given to assessing empirical studies of current knowledge of barriers to 3D printing adoption. This paper provides a comprehensive literature review on the key barriers to 3D printing in construction. In this study, the Preferred Reported Item for Systematic Review and Meta-Analyses (PRISMA) guideline was adopted to report the systematic review of the relevant past empirical studies on the barriers hindering the implementation of 3D printing in the construction industry. A total of 36 barriers were identified during the review and classified into six (6) categories. Thirteen key barriers hindering 3D printing implementation in the construction industry were identified and discussed. This study contributed to the knowledge of the barriers hindering the adoption of 3D printing. It will enable the built environment professionals to make the right choice when it comes to how 3D printing can improve the sustainable delivery of buildings.

Keywords
3D printing, Additive manufacturing (AM), Adoption, Construction Innovation, Construction industry.

1. Introduction

The construction industry is one of the largest industries in the world and has undergone significant advancements in recent decades, including the exploration of 3D printing. This modern technology, also known as additive manufacturing (AM) (Samuel et al., 2013; Tay et al., 2017), has the potential to improve current construction techniques, and its adoption is gaining momentum in the industry. 3D printing, as described by (Kazemian et al., 2017; Ngo et al., 2018; Pacillo et al., 2021; Tay et al., 2017; Xia et al., 2019), is an advanced layered material joining technique that allows producing complex and diverse structures based on 3D computer-aided-design (CAD) models without the need for tooling, dies, or fixtures. This modern technology can convert a computer design model into a tangible object. However, despite recent advancements in automated 3D printing systems, it is evident that some barriers hinder 3D printing's wider acceptance in the construction industry. For example, the size of the printer, building site obstructions, logistical burden of 3D-printed construction, and lack of codes and standards regulations in the green building (GB) movement, as highlighted by (Guamán-Rivera et al., 2022; Guamán Rivera et al., 2021; Jagoda et al., 2020; Tahmasebinia et al., 2018).

Much research on 3D printing innovations has been undertaken over the last few decades to comprehend the recent developments, future possibilities, and problems of large-scale use of 3D printing in building projects. Due to its potential for automation, formwork elimination, construction waste reduction, and geometrical precision improvement, 3DP has much promise for applications in the construction sector. To be compatible with the technology, materials used in 3D printing must fulfil specific requirements. According to (Camacho et al., 2018), cementitious materials, metallic materials, and polymer materials are the most often used materials in 3D printing. The current research on 3D printing focuses on other materials like cementitious materials (Huang et al., 2013; Paul et al., 2018; Soltan & Li, 2018), polymer materials (Ju et al., 2017; Panda et al., 2017; Yao et al., 2019) and metal materials (Buchanan & Gardner, 2019; DebRoy et al., 2018; Frazier, 2014). The 3D printing process involves the input process of fresh materials into the 3D printing machine and the output process of a 3D-printed object. 3D-printed structures can be produced either on-site or offsite. On-site 3D printing necessitates transporting the 3D printing machine, which can be challenging and expensive (Maskuriy et al., 2019). Offsite manufacturing is also known as prefabrication. The components are 3D-printed in a factory and then moved and installed on-site in prefabrication. This was the situation with Dubai's 3D-printed workplace. The properties of 3D printing include printability, pumpability/workability, extrudability, buildability, open time, shape retention factor, and scalability.

This paper identifies and addresses the key barriers to adopting 3D printing in construction. To achieve this, a systematic literature review was conducted to answer the following questions:

(I) What are the identified barriers to 3D printing adoption?
(II) What are the key barriers to 3D printing in construction?
(III) What are the recommendations for addressing the top barriers affecting 3D printing in construction?

Through this review, the authors aim to fill the research gap by collecting empirical studies on the barriers to 3D printing adoption, identifying and classifying the most significant barriers using a qualitative approach, and providing recommendations to address them. The paper begins with a brief introduction to 3D printing in construction, followed by a description of the methodology used in this research. Next, the barriers to adopting 3D printing in construction were reviewed, and their findings, recommendations, and conclusion were discussed.

2. Methodology

This study adopted Preferred Reported Item for Systematic Review and Meta-Analyses (PRISMA) guideline as seen in Fig. 1, to report the systematic review process. The description of the process involves the following;

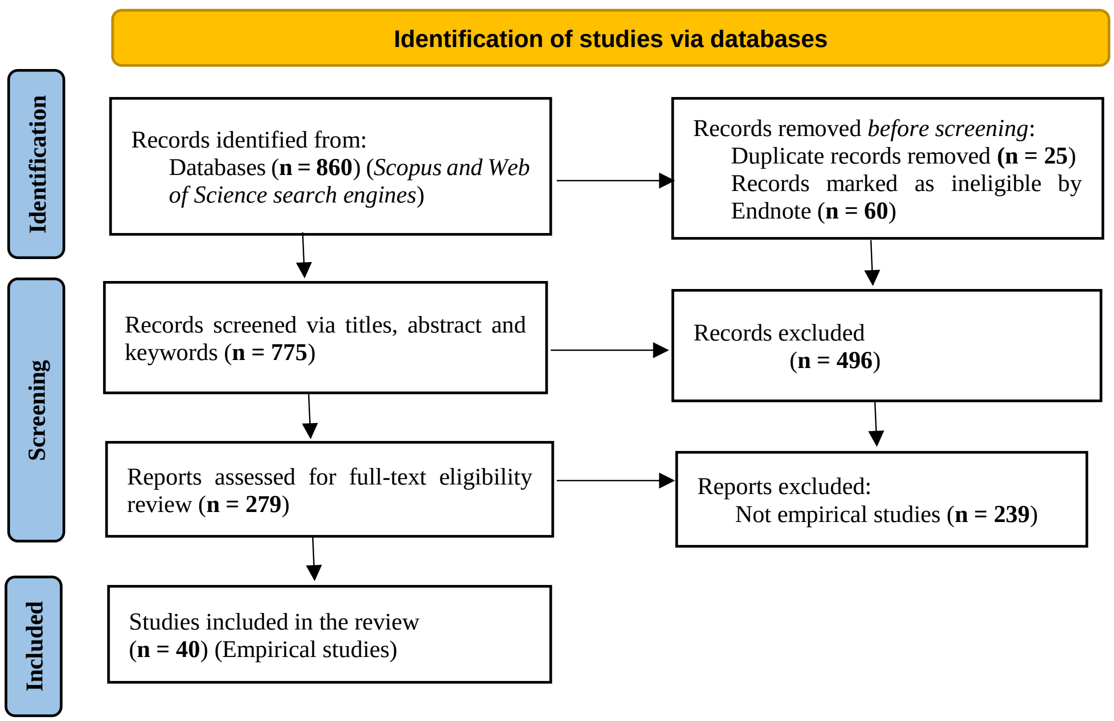

Fig. 1. PRISMA flowchart for the study selection procedure

The systematic literature review is focused on relevant past empirical studies on the barriers hindering the implementation of 3D printing in the construction industry. This review is exclusively based on relevant papers published in academic journals. A systematic literature search was based on two multidisciplinary databases of scientific research, Scopus, and Web of Science search engines. The following suited search keywords were used: "3D printing in construction" OR "additive manufacturing", AND "barriers". The initial search results of the combination of both databases cover 860 documents (Scopus: 617, WoS: 243). Then the search was limited to; “years = 2011-2022”, “document type = Research articles”, “subject areas = Engineering”, and “source type = Journal" to get current and relevant journals which resulted in about 279 papers. After filtering, 40 papers with empirical studies were found valid for further analysis. This research refers to published articles based on qualitative or quantitative data acquired from the industry using methods such as questionnaire surveys, interviews, and case studies, including experimentation when discussing empirical arguments concerning the barriers of 3D printing.

3. Results

3.1 Identification of 3D Printing barriers in construction

The first objective of this study was to identify the barriers to 3D printing in general. This objective was achieved by reviewing 40 academic publications that report empirical studies on 3D printing barriers. A total of 36 barriers were identified from reviewing several selected empirical studies. ***Table 1*** lists all the identified barriers from the selected papers reviewed.

3.2 Classification of 3D Printing barriers in construction

As shown in ***Table 1***, several barriers influencing 3D printing adoption have been identified through a systematic review of past empirical studies. To better understand the barriers to 3D printing, it is essential to classify them. The review suggests that 3D printing barriers can generally be grouped into six main categories: 3D printing process and material-related barriers, 3D printer and setup-related barriers, Design and characteristics of 3D-printed objects-related barriers, Construction and site management-related barriers, Environmental-related barriers, Regulatory and stakeholder-related barriers.

Table 1. Identification and classification of the barriers to 3DP in construction.

Group	Coding	Barriers	Reference
1		**3D printing process and material-related barriers**	
	B1	Printability	(El-Sayegh et al., 2020; Guamán-Rivera et al., 2022; Hossain et al., 2020)
	B2	Pumpability/workability	(Avinash et al., 2020; Guamán-Rivera et al., 2022; Hossain et al., 2020)
	B3	Extrudability	(Avinash et al., 2020; Guamán-Rivera et al., 2022; Hossain et al., 2020)
	B4	Buildability	(Avinash et al., 2020; El-Sayegh et al., 2020; Guamán-Rivera et al., 2022)
	B5	Shape retention factor	(Guamán-Rivera et al., 2022)
	B6	Open time	(El-Sayegh et al., 2020; Guamán-Rivera et al., 2022)
	B7	Scalability	(Sepasgozar et al., 2020; Tahmasebinia et al., 2018)
2		**3D Printer and Setup Related Barriers**	
	B8	Size of the printing system	(Guamán-Rivera et al., 2022; Tahmasebinia et al., 2018)
	B9	Size rate of the 3DP to the building object	(Tahmasebinia et al., 2018)
	B10	Suitability of the digital model for printing	(El-Sayegh et al., 2020)
	B11	Programming the machine in an efficient way	(El-Sayegh et al., 2020; Sepasgozar et al., 2020)
	B12	Positioning the printer platforms	(El-Sayegh et al., 2020; Guamán Rivera et al., 2021)
	B13	Motion programming (no effective pause and resume functions)	(Sepasgozar et al., 2020)
3		**Design and characteristics of 3D-printed objects related barriers**	
	B14	Layer-by-layer appearance	(Nerella et al., 2019; Ngo et al., 2018; Ning et al., 2021; Tay et al., 2017)
	B15	Void formation	(Hossain et al., 2020; Nerella et al., 2019; Ngo et al., 2018; Sepasgozar et al., 2020)
	B16	Anisotropic microstructure and mechanical properties	(Ngo et al., 2018)
	B17	Divergent from design to execution	(Ngo et al., 2018)
	B18	Structural integrity	(Avinash et al., 2020; El-Sayegh et al., 2020; Hossain et al., 2020; Tahmasebinia et al., 2018)
	B19	Reinforcement issues	(Hossain et al., 2020; Sepasgozar et al., 2020; Tahmasebinia et al., 2018; Vantyghem et al., 2020)

Group	Coding	Barriers	Reference
	B20	Exclusion of building services	(El-Sayegh et al., 2020)
4		**Construction and site management-related barriers**	
	B21	Cost estimation	(Bosch-Sijtsema et al., 2021; El-Sayegh et al., 2020)
	B22	Construction site setup	(El-Sayegh et al., 2020)
	B23	Obstacles to the construction site	(Guamán Rivera et al., 2021)
	B24	The logistical burden of 3D-printed construction	(Jagoda et al., 2020)
	B25	Full-size of structure	(Guamán-Rivera et al., 2022; Hossain et al., 2020; Sepasgozar et al., 2020)
5		**Environmental-related barriers**	
	B26	Insufficient demand for mass customization in construction	(Ning et al., 2021)
	B27	Insufficient environmental impact	(García-Alvarado et al., 2020; Ning et al., 2021)
	B28	Adverse environmental impact: discharge of harmful substances or emission	(Ning et al., 2021)
	B29	More susceptible to changes in environmental conditions	(Jagoda et al., 2020)
6		**Regulatory and stakeholder-related barriers**	
	B30	Lack of codes and standards regulations	(Bosch-Sijtsema et al., 2021; El-Sayegh et al., 2020; Jagoda et al., 2020)
	B31	Insufficient intellectual property protection	(Ning et al., 2021)
	B32	Lack of competence	(Bosch-Sijtsema et al., 2021)
	B33	Requirement of skilled workers	(Bosch-Sijtsema et al., 2021; El-Sayegh et al., 2020; García-Alvarado et al., 2020; Hossain et al., 2020; Tay et al., 2017)
	B34	Reduced sustainable employment	(El-Sayegh et al., 2020; Jagoda et al., 2020; Ning et al., 2021)
	B35	Scepticism about the potential of 3D printing	(Bosch-Sijtsema et al., 2021; El-Sayegh et al., 2020)
	B36	Unclear financial performance over the life cycle	(Bosch-Sijtsema et al., 2021; Ning et al., 2021; Tay et al., 2017)

4. Discussion

The 36 barriers of 3D printing identified in this review are grouped into six (6) main categories:

Group 1: 3D Printing Process and Material-Related Barriers

This category of barriers is related to the physical properties of materials and the printing process itself. Factors such as printability, pumpability/workability, extrudability, buildability, shape retention factor, open time, and scalability are crucial in 3D printing. For instance, some materials may not be compatible with certain printers, while others may require pre-treatment to be printable. Some materials may not be easily workable or pumpable, which could make the printing process more challenging (Guamán-Rivera et al., 2022; Hossain et al., 2020).

Group 2: 3D Printer-Related Barriers

This category of barriers is associated with the 3D printer itself, such as its size, printing rate, and suitability for the digital model being printed. For instance, larger structures require larger printers, which may not be available or affordable. Additionally, some printers may not be fast enough to meet project timelines, which could lead to delays. (Guamán-Rivera et al., 2022; Tahmasebinia et al., 2018) studied the effect of printer size and printing speed on the productivity of 3D printing in construction.

Group 3: Design and Characteristics of 3D-Printed Objects-Related Barriers

This category of barriers is related to the design and characteristics of the printed object itself, such as layer-by-layer appearance, void formation, anisotropic microstructure and mechanical properties, and divergences from the intended design. For instance, the layer-by-layer appearance of 3D printed structures may not be aesthetically pleasing, which could be a barrier to adoption. Additionally, 3D printed structures may have different mechanical properties compared to conventionally constructed structures. Ngo et al. (2018) examined the mechanical properties of 3D printed concrete and identified the challenges associated with anisotropic microstructure.

Group 4: Construction and Site Management-Related Barriers

This category of barriers is associated with the physical construction of 3D printed structures and the management of the construction site. Factors such as cost estimation, construction site setup, logistical challenges, and the size of the structure being printed are critical in this category. For instance, 3D printed structures may require a different approach to construction, which could lead to higher costs. Also, setting up the construction site for 3D printing may require specialized equipment and expertise. (El-Sayegh et al., 2020; Guamán-Rivera et al., 2022; Guamán Rivera et al., 2021) identified the key challenges associated with 3D printing in construction, including construction site setup, full-size of structure and obstacles to the construction site.

Group 5: Environmental-Related barriers

This category refers to barriers related to the environmental impact of 3D printing technology. This includes factors such as the insufficient demand for mass customization in construction, insufficient environmental impact assessment, adverse environmental impact, for example: discharge of harmful substances or emissions, and susceptibility to changes in environmental conditions (García-Alvarado et al., 2020; Jagoda et al., 2020; Ning et al., 2021).

Group 6: Regulatory and Stakeholder-Related Barriers

This category of barriers is related to the regulatory environment for 3D printed structures and the human factor involved in adopting and implementing 3D printing technology in the construction industry. Factors such as lack of codes and standards, insufficient intellectual property protection, need for more competence, reduced demand for workers, scepticism about the potential of 3D printing, and unclear financial performance over the life cycle are crucial in this category. For instance, the lack of clear codes and standards for 3D printing in construction may make it difficult to obtain regulatory approval for 3D printed structures. Stakeholders may be sceptical about the potential of 3D printing, which could lead to resistance to adoption. (Bosch-Sijtsema et al., 2021; El-Sayegh et al., 2020; Jagoda et al., 2020) identified the key barriers to the adoption of 3D printing in construction, including regulatory challenges and stakeholder scepticism.

Key identified barriers

The 13 key barriers of 3D printing are based on the most reported barriers in the selected reviewed literatures, and they are B33, B19, B18, B1, B2, B3, B4, B14, B15, B25, B30, B34, and B36.

B33: Requirement of skilled workers

One of the barriers to 3D concrete printing is that it needs experienced workers with prior expertise in integrating robotic and civil work (Tay et al., 2017). The need for additional skills (in design, manufacturing, materials, testing.) impeding adoption, development skills of current workers, training future generations, consumer education, and educational awareness. However, with the rising acceptance of 3DCP (3D concrete printing), the workforce will require training to cope with the new working procedures of 3DCP or may choose to move to other employment (Mathur, 2016; Tay et al., 2017). According to the workshop result reported by (Bosch-Sijtsema et al., 2021), the participants of the workshop emphasized a lack of competency and the need for training in digital technologies, as well as new competencies that would need to be introduced from diverse disciplines and industries to include new technologies such as 3D printing.

B19: Reinforcement issues:

Another barrier to 3D printing in concrete construction is the difficulty in using reinforcement; since cement components are poured out of the 3D printer nozzle, it is impossible to insert reinforcement within the building. As a result, the tensile strength of concrete becomes a limiting element in constructing a 3D-printed house (Hossain et al., 2020; Sepasgozar et al., 2020; Tahmasebinia et al., 2018). However, with 3D printing, adding steel reinforcement automatically is more complex.

B18: Structural integrity

This is another barrier; since 3D printing models do not have the exact attributes of full-size structures, the structural performance is affected. A good 3D-printed structure depends on the concrete of high quality. However, according to (Berman, 2013), it has been discovered that the quality of printed parts is brittle, making it challenging to print load-bearing components. The multilayer structure is expected to be anisotropic due to the likelihood of voids accumulating between filaments, which impairs structural strength (Buswell et al., 2018). Several studies have revealed that the strength and stability of printed items manufactured using conventional printing materials (plaster) may hinder the technology from being employed in large-scale models or structures (Wu et al., 2016).

B1: Printability

The easiness with which the material is pumped out of the printer's nozzle (Guamán-Rivera et al., 2022; Hossain et al., 2020). The material must be consistently pushed out of the 3D printer's nozzle.

B2: Pumpability/workability

Pumpability is the ease with which the material is pumped through the 3D printer's pump. The pumpability and printability of concrete are greatly influenced by its workability and mix percentage (Uppalla & Tadikamalla, 2017).

B3: Extrudability

The material can be placed in the extrusion system regularly and uninterruptedly (Avinash et al., 2020; Hossain et al., 2020). The nozzle size is critical for concrete extrudability. It is primarily influenced by the mixture's quantity and distribution of dry components, necessitating suitable fine aggregate rheological characteristics (Kosmatka et al., 2008). According to (Lim et al., 2012), the particle size distribution (binder and aggregate) affects the extrudability of printed concrete.

B4: Buildability

The ability of the printed layers to retain the subsequent layers on top of them without failing (Guamán-Rivera et al., 2022). The material to be used in 3D printing must harden fast. Concrete buildability after extrusion results in issues such as lower layer fails, deformations concerning the time gap between layers, and creating cold connections between layers (Guamán-Rivera et al., 2022).

B14: Layer-by-layer appearance

Another barrier is the 3D printing process's layering effect, which generates uneven surfaces with the potential of cavities between the layers. This is one of the 3DCP's significant barriers (Ngo et al., 2018; Ning et al., 2021; Tay et al., 2017). In layer-by-layer deposition procedures, an absence of a compaction method leads to excessive air voids. As a result, the air-void structure in 3DPC is more extensive, which lowers the binding strength between the layers (Nerella et al., 2019). Also, layer-by-layer 3DPC deposition typically results in numerous interfaces caused mainly by air-void presence between succeeding filaments (Wolfs et al., 2019).

B15: Void formation

Sepasgozar et al., (2020) reported that one of the three main barriers to 3D printing is void formation, that is, the availability of voids in concrete. There is the possibility of voids in the layer due to the layer effect of the 3D printing process (Hossain et al., 2020). An entrained air void directly impacts the workability and durability of cementitious materials (Fonseca & Scherer, 2015). Furthermore, the air void between layers will likely weaken the bonding between filaments, affecting 3DPC performance under challenging situations (Ma et al., 2020). For instance, for every 1% increase in air content, high-strength concrete loses around 5% of its compressive strength (Lazniewska-Piekarczyk, 2016). Additionally, the air-void size distribution has a considerable influence on the performance of cementitious materials.

B25: Full-size structure

Another issue of automatic printing of a full-size construction is the danger of losses or accidents if there is an error in the design of 3D models or print settings (Hossain et al., 2020).

B30: Lack of codes and standards regulations

This is also a barrier since there are no defined guidelines for using 3D printing in construction, making it challenging to deploy the technology in a way that conforms with all building codes and regulations (Bosch-Sijtsema et al., 2021;

El-Sayegh et al., 2020; Jagoda et al., 2020). Additionally, defining codes, standards, and specifications for these sustainable structures, especially public safety code requirements, adds to the problems of large-scale 3D printing adoption. The absence of legislation governing 3D-printed buildings presents a barrier for additive-manufactured houses, as any construction activity would be required to follow such a code of conduct in the case of an accident or fatality (Strauss, 2013).

B34: Reduced sustainable employment

One of the barriers to 3D printing is the reduced labour demand due to insufficiently skilled workers in 3D printing (Jagoda et al., 2020; Ning et al., 2021). There need to be more suitably skilled individuals in additive manufacturing and more possibilities for teamwork and idea exploitation (Mehrpouya et al., 2019). As these jobs are replaced by automation, labour force participation rates are expected to decrease.

B36: Unclear Financial Performance over the Life Cycle

There is also a general need to understand the economic benefits that this technology may give. Adding 3D printing to a project's life cycle cost analysis (LCCA) allows an alternate option to be assessed for maximum net savings (Tay et al., 2017).

5. Conclusions and Recommendations

This study presented lessons that have been learned in the previous decade from the selected articles, a systematic review of the literature was conducted, particularly the articles focusing on the barriers hindering the implementation of 3D printing in the construction industry. Those articles were analyzed and discussed. 36 barriers were identified and grouped into six distinct groups. A total of 13 barriers to 3D printing were acknowledged as the key barriers. Due to the rising adoption of 3D printing, it is recommended that existing workers should enrol in training to acquire skills on how the 3D printing system works. The widespread use of 3D printing would result in the loss of numerous construction jobs, particularly in low-skilled occupations. However, the implementation of 3D printing into the life cycle cost analysis (LCCA) of a project allows for the consideration of an alternate option for optimum net savings. This will help in solving unclear financial performance over the life cycle. For the layer-by-layer effect, the impact can be avoided by using thin layers; although, building the entire structure will require extra time and energy. Controlling the air-void structure remains a considerable difficulty. However, adding anti-foaming agents (AFA) can also help reduce unnecessary air-void content in 3DPC. To increase buildability, a square nozzle is commonly used, and it is typically programmed so that the nozzle's orientation is visible to the tool direction. Also, for optimal pumpability, a suitable mix design necessitates a high cement content or, more accurately, a high paste content. Adding more water and 1% to 2% of superplasticizer will make the mix more flowable and improve extrudability. Also, building codes and regulations are urgently required, although some countries are already responding. This review can be useful to scholars and built professionals in helping them to understand the intended barriers which they may encounter, thus knowing how to avoid them.

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