Motives and Barriers for Offsite and Onsite Construction 3D Printing

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Abstract –

This study aims to compare between onsite and offsite construction 3D printing (C3DP). For this purpose, the Systematic Literature Review approach (SLR) was employed. The review which was based on studying 48 sources identified six categories to classify the motives and barriers for the two C3DP techniques; cost, transportation, design flexibility, workers and materials, production process, and environmental considerations. The literature identified the cost as the main factor that influences the choice between the two techniques. The presented list of motives and barriers is helpful to support decision-making in C3DP projects.

Keywords –

Additive Manufacturing, 3D Printing, Construction Management, Modular Construction, Offsite Construction, Literature Review.

1 Introduction

Three-dimensional printing (3D printing) and Additive Manufacturing (AM) are synonymous terms referring to a process that builds objects layer by layer from 3D model data, deviating from subtractive manufacturing methodologies [1]. The origin of this technology can be traced to Japanese researcher Hideo Kodama's writings, with Charles Hull developing the first commercial 3D printing machine, the Stereolithography fabrication system [2]. Over time, 3D printing has transitioned from producing prototypes to facilitating the serial production of parts across diverse fields, resulting in the global 3D printing sector's revenue exceeding $10 billion in 2021, with expectations to surpass $50 billion by 2030 [3,4].

The construction industry, characterised by challenges such as low productivity, safety concerns, and environmental issues, can benefit significantly from 3D printing applications [5–8]. Its capacity to create customized structures not easily achievable with conventional methods, coupled with enhanced design flexibility and adaptability to changes, positions 3D printing as a transformative solution [6,9–11]. Furthermore, its ability to save time in design and construction processes makes it an ideal choice for emergency shelters [12]. Despite the substantial initial capital required for 3D printing equipment, cost savings in materials management, labour, and other associated expenses contribute to its economic feasibility [6]. Reports suggest that using 3D printing in housing construction can result in savings of up to 35% of the total house price in the UK [13].

Beyond economic advantages, 3D printing offers substantial sustainability benefits. Opportunities to reduce waste generation, employ eco-friendly materials, and decrease greenhouse gas emissions contribute to a more environmentally friendly construction approach [14,15]. Socially, the comfort, safety, and working conditions of construction workers can be improved through the application of 3D printing technology [12,16,17].

Construction 3D Printing (C3DP) encompasses two distinct approaches: onsite and offsite. Onsite C3DP involves the direct fabrication of building units at the designated construction site, where 3D printers are strategically positioned, autonomously producing the structured building with automated control—a process resembling typical industrial production. In contrast, offsite C3DP takes place away from the construction site, with units or components manufactured in a separate factory using automated 3D printers. These prefabricated components are then transported to the construction site for assembly, marking a clear distinction between industrial products and construction products. The onsite method emphasizes in situ construction, allowing for immediate and tailored building creation, while the offsite approach prioritizes prefabrication within a controlled environment before assembly at the construction site [18,19]. Figure 1 distinguishes between the processes of offsite and onsite C3DP.

The growing interest in Construction 3D Printing (C3DP) is evident in the existing literature, which extensively covers various aspects such as materials, the automated process, challenges, and usability across different project types and locations [12,20,21]. However, there has been a notable gap in the exploration of the distinctions between offsite and onsite C3DP. Delving into this topic and comprehending the motivations and barriers associated with each type would contribute significantly to the existing body of knowledge. This exploration is crucial not only for advancing academic research but also for providing valuable insights to practitioners, clients, decision-makers, and companies involved in C3DP projects. Understanding the potential outcomes and implications of choosing between offsite and onsite C3DP can inform strategic decision-making, leading to the enhancement of project performance. Consequently, this study aims to bridge this gap by offering a comprehensive comparison of the factors influencing both offsite and onsite C3DP.

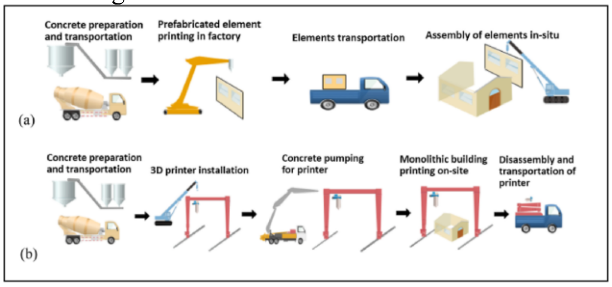

Figure 1. C3DP approaches (a) Offsite, and (b) Onsite [19,22].

2 Research Methodology

In pursuit of the study's objectives, the methodology utilized was the Systematic Literature Review (SLR). The SLR was chosen to guarantee an impartial selection of sources, transparency, and the ability to repeat the process [23–25]. Following the guidelines of the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA), the SLR is structured around three primary phases: identification, screening, and eligibility [25]. The procedural steps involved the exploration of sources using the following terms:

("3d Printing" OR "3D Print" OR "additive manufacturing" OR "additive construction" OR "concrete print" OR "concrete printing") AND construction AND (modular OR modularity OR offsite OR "off-site" OR "off site" OR onsite OR "on site" OR "on-site").

As depicted in Figure 2, the search yielded a total of 191 sources. Among them, 32 studies were either unrelated to construction or did not directly address 3D Printing (for instance, papers focusing on 3D printing in other fields or listing it among various applications in construction). After searching the keywords, titles, and abstracts, a full-text search was conducted. During this phase, any results lacking information on onsite and offsite 3D printing were excluded. Upon completing the eligibility phase, the final count of included studies stood at 48.

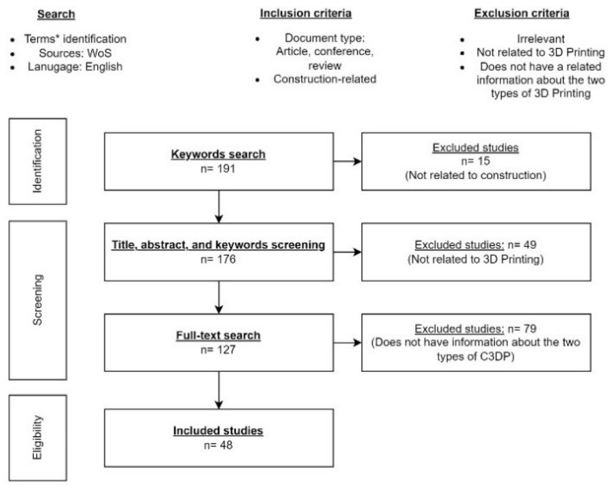

Figure 2. The SLR approach

3 Results

The results of the study were organized based on five main categories as explained below:

3.1 Cost

The cost of the two types of C3DP has received the highest attention in the literature. Yang et al [26] presented a detailed comparison between the expected cost in conventional construction, offsite, and onsite C3DP projects. Based on their study, the time cost of C3DP is an important motive that needs further investigations to identify its impact. This is because it is one of the main factors that affect the company's expenses and motivates its transition toward 3D Printing. Their study also provided the different composition of the 3D printing cost in onsite and offsite projects. Offsite C3DP cost consists of printing stage cost and assembly stage cost. The printing stage cost includes management costs, manufacturing costs, printing costs, transport costs, and value-added tax. The assembly stage cost includes construction and installation expenses, procurement expenses of equipment, and other expenses for engineering construction. Onsite C3DP cost consists of procurement expenses of equipment, construction and installation expenses, and other expenses for engineering construction. In turn, Besklubova [27] focused on the comparison between logistics costs in onsite and offsite C3DP. The study identified different factors that affect the cost in the two types of projects such as the proximity of the supplier, the size of the building, and the need for customization. It highlights material transportation costs as the dominant factor in logistics expenses, with equipment transportation costs being less significant for low-story buildings. More specifically, Onsite 3D printing proves economically superior for low-story buildings situated near suppliers, while offsite is advantageous for high-rises and distant suppliers. Alternative 3D printer technologies, notably the robotic arm, demonstrate a remarkable 96% cost reduction for onsite printing. Offsite 3D printing excels in customized or remote projects, offsetting high transportation expenses. Conversely, onsite 3D printing is cost-effective for nearby projects with minimal customization. Material transportation costs dominate logistics expenses, making onsite 3D printing more feasible for low-story buildings.

3.2 Transportation

Transportation plays a pivotal role in the dynamics of 3D printing construction, both onsite and offsite. The type of printing method, the size of the project, available transportation infrastructure, and the location of the construction site all play a role in determining the most appropriate transportation strategy. Onsite printing eliminates numerous logistical processes and preparation tasks associated with traditional construction methods [28]. As a result, onsite production allows for the immediate construction of larger structures without transportation concerns [29]. Additionally, the use of prefabricated elements, often results in damaged parts during transit, requiring on-site repairs and increased labour. This explains why some contractors prefer on-site printing to avoid damages, over-engineering, and added costs associated with transportation [29,30]. However, it may be less stable due to changing environmental conditions [29]. Onsite 3D printing is highly dependent on weather conditions due to the impact on the drying and shrinkage processes [29]. Moreover, accidents while transporting the printer may happen [12,29,31].

In turn, offsite 3D printing introduces complexities due to increased transportation needs, impacting costs. Besklubova [27] found that transportation expenses could nearly double in the offsite scenario when compared to onsite printing. Despite this, offsite construction offers advantages such as improved process control, part quality, safety, and simultaneous manufacturing and construction schedules [12,29]. However, transportation constraints, especially in remote environments, remain a challenge. The impact of weather on the transportation routes is also nonnegligible [12].

3.3 Workers and Materials

On-site and off-site C3DP present distinct labour and safety considerations. On-site printing helps reduce the demand for on-site labour by theoretically allowing the printing of entire building structures. While traditional construction roles may decrease, the need for specialized personnel to install, calibrate, and oversee 3D printing equipment remains. As a result, onsite 3D printing might be faced with the challenge of the experts' availability or the increased cost due to the need to provide training for workers [31–33].

Automation in on-site printing is expected to enhance safety by reducing hazardous tasks and providing a controlled environment. In contrast, off-site 3D printing involves prefabrication in a factory, potentially impacting on-site labour less than traditional methods. Safety benefits are attributed to lower risks and reduced congestion in a factory setting [12,29]. It is worth mentioning here that safety improvement in both types of systems is one of the main advantages of 3D Printing; contrastingly, a reduction in labour force and job opportunities may lead to political instability [31].

Concerning materials, using printable material remains the topic that received the highest attention in the literature for both types of 3D printing. The research in this field covered several aspects aiming at utilizing locally sourced materials when accessible, minimizing the need for material transportation to remote areas and reducing inventory levels [5,8,34,35]. Onsite 3D Printing might help maintain natural local materials. However, the availability of local printable materials remains very challenging [12,19,31]. Additionally, the choice between offsite and onsite 3D printing heavily depends on the type of material. For instance, concrete is widely used in offsite 3D printing due to versatility, strength, and availability. Prefabricated 3D printed components' performance can be optimized using reinforcement or specialized mixtures to improve extrusion and layering and ensure proper flowability and structural integrity. They can also integrate additives such as fibres to improve crack resistance during transportation and enhance workability [12,19,35].

3.4 Design Flexibility

Design flexibility allows C3DP to adapt to the needs of every project. The ability to modify, alter, and adjust the design details in a significant reduction in costs, materials, and labour during manufacturing [31,36,37].

C3DP offers more flexibility in modelling compared to traditional construction methods [20]. By providing the opportunity to adjust to every conceptual design and location, C3DP brings solutions to the local environment, positively impacting the regions [12,31].

Design flexibility plays a pivotal role in both on-site and off-site C3DP. Some of the advantages include the capacity to create customized elements, different shapes, features, and textures. C3DP has proven to be a valuable competitor to prefabrication in terms of cost-effectiveness and time efficiency. Simultaneously, C3DP can develop shapes that would be difficult or impossible to create using traditional methods. The use of specialized software and tools to optimize design is emphasized, allowing C3DP to optimize design and reduce risks during production [19,35,38].

Another advantage of C3DP, in comparison with conventional construction, is its ability to manufacture complex designs [20]. Design flexibility has positive effects in terms of efficiency and process time [39]. Further considerations of the design reflect on the use of local materials and labour. The C3DP manufacturing process addresses challenges related to skill development and technology adoption [40].

3.5 Production Process

C3DP increases efficiency and productivity compared to conventional construction. It can be used to automate many tasks involved in the production process. An advantage of C3DP is the capacity to print entire wall elements or other structural components in one piece, reducing the need for traditional construction methods such as formwork and scaffolding [41–44].

During the production process, several distinctions between on-site and off-site are addressed. On-site C3DP shows a significant improvement in terms of time efficiency compared to traditional construction methods, based on the elimination of assembly work and the fact that C3DP elements can dry while other activities are performed simultaneously. Several authors reflect on the potential of C3DP to be used in remote locations, offering a solution for housing shortages in those areas. Remote environments pose a challenge for C3DP due to local weather conditions and logistical complexities. On the other hand, off-site C3DP has the potential to become a solution as a manufacturing method for pre-fabricated modular buildings [12,19,43].

Another advantage of C3DP in off-site manufacturing is the flexibility during the design and production process, allowing builders to create different geometries and automate C3DP elements for mass production [29]. Off-site C3DP manufacturing allows builders to control external conditions for better results during printing [19,43].

3.6 Environmental Considerations

Concerning environmental impact, only a few studies have evaluated the environmental life cycle of C3DP [12]. The primary concern regarding the environmental impact of C3DP lies in material development, with concrete representing a significant percentage of CO2 emissions in C3DP [26,27,29,45]. The creation of new materials is crucial for the success of this technology [40].

New applications for C3DP depend on material properties, such as strength and durability. Some authors reflect on the potential benefits of C3DP in reducing waste and the environmental footprint of concrete [45]. The use of this technology allows builders to develop materials locally by using local aggregates. C3CP also provides the opportunity to cycle waste streams from other industries, improving circularity in the system [46].

A reduction in environmental and economic impact is evident. More studies need to be developed around the environmental life cycle assessment of C3DP materials [47]. C3DP optimizes the construction process and reduces material usage, time, and transport, directly impacting a reduction in CO2 emissions [26,27,48].

Further research on the environmental impact of C3DP needs to be conducted to reflect the differences between on-site and off-site printing. Both scenarios represent an improvement in environmental impact [19]. On one side, off-site printing allows developers to control environmental conditions and reduce risks during manufacturing [19,35]. On the other hand, several limitations around on-site C3DP are illustrated, including environmental conditions, equipment and material transportation, the use of a mixing system, and material preparation at the location, posing challenges to the implementation of C3DP on-site [38,41,48].

4 Discussion and Conclusions

3D printing in construction represents a ground-breaking innovation that aims to build more efficient, flexible, and sustainable production practices in the construction sector. As the technology continues to evolve and gain wider adoption, its influence on the way we conceptualize, design, and construct structures is expected to expand significantly. This paper aims to support the decision-making process in the construction of 3D printing projects. This is by conducting a review of the related literature to compare the onsite and offsite 3D printing techniques. The analysis of the results of this study revealed various motives and barriers for both techniques (as shown below in Table 1 for Onsite C3DP and Table 2 for Offsite C3DP). These motives were organized based on six categories: cost, transportation, workers and materials, production process, design flexibility, production process, and environmental considerations.

Table 1. Onsite C3DP Motives and Barriers

Category	Motives	Barriers
Cost	Reduction of components transportation costs minimization of preparation tasks	Lack of redundancy in process and hardware, specialized equipment costs, maintenance and repair costs
Transportation	Elimination of the risk of damage to prefabricated components during transportation, minimization of waste, conservation of natural resources	Potential damage during the printer's transit, shortages of skilled labour, workers' safety considerations in managing and maintaining 3D printing equipment, need for training to build skills
Workers and Material	Enabling larger structures to be built without the need for transportation, improvement of quality, production speed, and site safety	Component design limitations in terms of size and complexity, interruptions if 3D printing experiences technical issues, quality control challenges
Design Flexibility	Onsite modification	Weather dependency leading to interruptions, noise pollution, dust, and debris on-site disruption
Production Process	Elimination of assembly work	Interruptions if 3D printing experiences technical issues, quality control challenges
Environmental Considerations	Reduction in carbon transportation emissions, use of sustainable materials contributing to environmentally conscious practices	Weather dependency leading to interruptions, noise pollution, dust, and debris on-site disruption

Table 2. Offsite C3DP Motives and Barriers

Category	Motives	Barriers
Cost	Reduced labour costs, reduction in transportation expenses, ability to reach remote areas without transporting the printer, avoiding stoppages due to needed printer maintenance, especially in remote areas	Transportation expenses for moving components from off-site facilities to construction locations, assembly costs (e.g., crane costs), risk of damage to prefabricated components during transportation, transportation limitations for large-scale items/components/machines
Transportation	Reduction in the need for transporting raw materials and printers to multiple construction sites, ability to reach remote areas without transporting the printer, avoiding stoppages due to needed printer maintenance, especially in remote areas	Worker safety concerns in the factory, extra cost for training in the factory
Workers and Material	Availability of workers and stability of staff, reduction of material waste by optimizing the production	Design constraints for transportation, design limitations on complexity and component size

	process, ability to standardize items	
Design Flexibility	Ability to standardize items	Dependency on off-site facilities
Production Process	Repeatability and ability to make continuous improvement, improved site safety, scalability to accommodate changes in project scope	Risks related to production delays, supply chain disruptions, or changes in project requirements
Environmental Considerations	Reduction in waste generation and energy consumption	Weather dependency during the transportation or assembly, carbon transportation emissions

Analysing Table 1 and Table 2 shows that some of the presented factors are not exclusively related to 3D printing. They can be considered generally when comparing onsite and offsite practices in construction. Examples of these factors cover safety concerns and logistics arrangements in factory environment or onsite.

The review of the literature showed that cost is a significant factor in the decision of whether to use onsite or offsite 3D printing construction. However, it is not possible to say definitively that one technique is more cost-effective than the other, as the choice depends on a variety of factors, including the location of the project, the size of the project, the need for customization, the need for standardized components, weather conditions, quality control measures, safety considerations, and the availability of human resources.

For example, Onsite C3DP is generally more cost-effective for low-story buildings located near suppliers, while off-site printing is typically more economical for high-rise buildings and projects in remote locations.

In addition to cost considerations, it is important to weigh other factors, such as the potential to empower local human resources and create new job opportunities for local citizens. This is particularly important in areas that require development strategies.

The current study has several limitations. Firstly, it is based on a review of the literature and does not include findings from other methods, such as interviews. Secondly, the study focuses on listing the main motives and barriers without detailing the specific scenarios behind these results. For example, the study does not provide a detailed comparison between the cost of different items in both techniques or the emissions associated with each technique. Thirdly, the study does not focus on a specific location or, printing method, or material. Neither does it focus on a specific type of material. The presented comparison between offsite and onsite 3D printing may cover many other items if focusing on concrete, for instance. Examples of these factors include the ability to improve the mechanical performance of concrete, availability of additives, possibility of reinforcement, recyclability, and usability of materials at the end of the project life. Future studies should address these limitations by focusing on specific materials or using a variety of methods, including case studies, to provide more detailed and nuanced insights into the decision of whether to use onsite or offsite C3DP.

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