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DRIVERS FOR ADOPTING 3D PRINTING TECHNOLOGY IN TURKIYE

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Abstract

This study investigates the factors driving the adoption of 3D printing technology in construction industry, focusing on Türkiye and developing EU countries. A comprehensive literature review identified 27 key drivers, which were evaluated through a survey of 106 professionals using Relative Importance Index (RII). Results reveal that faster construction, lower rate of site accidents and fatalities, and reduction in material waste are the most significant drivers, while freedom in design due to less strict standards was found to be the least important. The research emphasizes the need for targeted initiatives to enhance the integration of 3D printing in construction projects.

Introduction

As one of the least digitalized industries, construction deep-rooted culture that resists change (Young et al., 2021). This dependence on manual methods complicates project management, leading to inefficient processes (Delgado and Oyedele, 2021; Bello et al., 2021). The slow adoption of digital technologies has contributed to issues like poor cost management, delays, low in productivity (Niksa et al., 2007).

Innovative technologies offer a promising way to address such challenges. By adopting advanced tools, construction companies can reduce material waste, accelerate project timelines, and enhance desing flexibility (Labonnote et al., 2016). These groundbreaking innovations have the potential to transform traditional construction methods, leading to a more efficient, sustainable, and forward-thinking future for the industry.

3D printing, or additive manufacturing (AM), stands out as a key technology. This computer-aided process builds structures layer by layer from a 3D model (Ali et al., 2022). Initially used for rapid prototyping, it has evolved into a full-scale production method across various sectors (Kellen et al., 2017; Egger and Masood, 2020; Saade et al., 2020).

In construction, 3D printing automates traditional building processes, bringing significant advantages over conventional methods (Buswell et al., 2008; Lim et al., 2012). By reducing labor-intensive practices and promoting sustainability, it stands to revolutionize the industry (Zuo et al., 2019). It improves efficiency, enhances design flexibility, curtails material waste, and allows for prestressing, repair, and reinforcement (Buchanan and Gardner, 2019). One of its most notable benefits is its ability to significantly reduce on-site assembly times (Hou et al., 2022). Additionally, 3D printing supports economic and ecological sustainability (Tu et al., 2023).

The adoption of 3D printing in construction, however, is influenced by unique factors specific to each country. Government initiatives promoting technological innovation and sustainable construction practices have notably accelerated adoption in the Netherlands, China, and the United Arab Emirates (Pessoa et al., 2021). For instance, Dubai's "Dubai 3D Printing Strategy" aims to establish the city as a leader in 3D printing by 2030, with projects like the world's first 3D-printed office building (Rajan et al., 2018). Similarly, China has showcased the technology's potential with projects like the 3D-printed pedestrian bridge in Shanghai (Yu et al., 2024).

Despite global advancements, research focusing on the Turkish construction industry remains limited. This study aims to fill this gap by identifying the unique drivers for adoption of 3D printing in Türkiye and other countries that share similar characteristics and development status. In this regard, 27 distinct drivers were identified through a comprehensive literature review, offering insights into how this technology can be integrated into these regions. Recognizing these drivers will help develop tailored strategies to support the successful implementation of 3D printing in Türkiye and similar countries, paving the way for more efficient, sustainable, and innovative construction practices.

The remainder of this paper is structured as follows. Section 2 provides an overview of 3D printing technology, Section 3 details the research methodology, Section 4 discusses the results, and Section 5 concludes with key findings and future directions.

3D Printing Technology

This section delves into the key trends shaping 3D printing technology within the construction sector. It provides an in-depth summary of the diverse materials and techniques used in 3D printing.

For a material to be suitable for 3D printing, it must meet requirements related to workability, strength, and sustainability. Workability involves the material's ability to be extruded or layered without disrupting the printing process (Buswell et al., 2018). The material must also gain sufficient early strength to support subsequent layers. Sustainability is increasingly important, with many projects prioritizing eco-friendly materials (Malaeb et al., 2015). Cementitious materials, including concrete and mortar, are the most commonly used in construction 3D printing due to their availability, affordability, and suitability for large-scale projects. These materials must be carefully formulated to ensure they are fluid enough for extrusion while maintaining the strength needed to support the structure once hardened. Research shows that balancing viscosity, setting time, and strength is essential for successful 3D printing (Kazemian et al., 2017). Polymers are commonly employed in 3D printing, particularly when flexibility, lightweight construction, or insulation are needed. Thermoplastics, which can be reshaped upon heating, are well-suited for additive manufacturing (Dizon et al., 2018). While less frequently used than cementitious materials or polymers, metals have gained traction in construction 3D printing, particularly for applications demanding high strength and durability. Metals such as steel and titanium are increasingly utilized in specialized projects, like structural components or fixtures. Technological advancements in methods such as selective laser melting (SLM) and electron beam melting (EBM) have enabled the precise layer-by-layer creation of metal parts (Herzog et al., 2016).

3D printing techniques, on the other hand, are evolving rapidly. Contour Crafting (CC) (Khoshnevis, 2006), concrete printing (Lu et al., 2019), and D-shape printing (Zhang et al., 2019), are among the most recognized methods. Additionally, innovations like selective binder activation, selective paste intrusion, and rock printing further expand the possibilities for large-scale construction applications (Lowke et al., 2018).

Contour Crafting (CC), introduced by Khoshnevis at the University of Southern California in 1998, is one of the most well-known AM techniques for construction. It uses cement-based pastes (Lim et al., 2012) and has been praised for producing higher surface quality compared to other methods (Khoshnevis and Dutton, 1998). CC operates with a gantry system, which moves along the x, y, and z axes, and utilizes an extrusion system for material deposition, including spackling compounds and clay (Khoshnevis, 2004; Khoshnevis et al., 2001). This system ensures smooth surface finishes, often enhanced by trowels attached to the extrusion mechanism (Hwang and Khoshnevis, 2005). Over time, the method has seen improvements, such as the introduction of sulfur concrete, which is particularly effective for applications like space construction, where extreme conditions demand high-strength materials (Khoshnevis et al., 2006). Research has also explored how factors like the cement-to-water ratio, fiber content, and chemical admixtures influence the bonding strength between layers, crucial for the structural integrity of large-scale printed buildings (Zareiyan and Khoshnevis, 2017; Ali et al., 2022).

Concrete printing emerged from research at Loughborough University in collaboration with Skanska. It integrates a robotic arm and a gantry system, offering better control over the printing process and enabling more precise geometries (Skanska, 2014). However, the materials used in concrete printing remain limited, with common choices including Portland cement, gypsum, and fly ash. Researchers are focused on optimizing material mixtures to enhance the performance of these materials in both academic and commercial settings (Ali et al., 2022). Notable advancements have included incorporating hydroxypropyl methylcellulose into sulphoaluminate cement to improve the compressive strength of extruded mortar (Ding et al., 2018). Concrete printing offers higher resolution than CC and typically requires secondary support materials and post-processing steps to remove supports (Ali et al., 2022). Material selection, especially aggregate size, plays a key role in preventing issues such as nozzle blockages, while also influencing the hydration heat of the cement (Ali et al., 2022).

D-shape printing utilizes powder-based materials and binder jetting systems (3D Printing Technology, 2024). In this method, liquid adhesives are deposited onto layers of cement powder, causing specific areas to solidify and bind together (Ngo et al., 2018). Unlike other methods, D-shape printing eliminates the need for external support structures as the unbonded powder itself provides support during the printing process (Perkins and Skitmore, 2015). This approach allows for the use of a variety of materials, including sand-like substances, and has the potential for less waste, as excess material can be reused while the resulting structures often have a natural stone-like appearance (Tibaut et al., 2016). D-shape printing has been demonstrated for creating full-scale building components from lunar soil, indicating its potential for applications in extreme environments, such as military infrastructure or space exploration, where traditional building materials are unavailable (Cesaretti et al., 2013). However, challenges such as the difficulty of cleaning the printed parts and issues related to in-situ printing remain to be addressed (Hussein, 2021).

The development of 3D printing techniques for construction has shown considerable promise in transforming the industry. Contour Crafting, concrete printing, and D-shape printing have unique strengths and challenges, offering potential solutions for a range of construction applications. The integration of robotic technologies and new material innovations further amplifies the potential of these methods, making large-scale, sustainable, and efficient construction more feasible (Zhang et al., 2018). In this vein, robotic arms, which can be mounted on mobile platforms, offer more flexibility in terms of space requirements but are still limited by their reach and ability to create sharp corners (Camacho et al., 2018). Newer robotic systems, such as cable robots, are gaining attention for their lightweight design and ability to produce complex geometries (Barnett and Gosselin, 2015). These systems also help address some of the challenges faced by traditional gantry-based approaches, such as space constraints and limited movement. As research and development continue, such innovative techniques are expected to play an increasingly important role in shaping the future of construction, enabling the creation of structures that are not only more complex and customized but also more environmentally sustainable (Kothman and Faber, 2016).

Methodology

This study aims to identify and analyze the perceptions of Turkish construction practitioners regarding the drivers affecting the implementation of 3D printing technology. The research methodology consists of four successive steps: questionnaire design, data collection, data analysis, and presentation of results.

Design of Questionnaire

The questionnaire design followed two key steps: a comprehensive literature review and a pilot study. The process began with an in-depth review of existing literature to identify the drivers influencing the adoption of 3D printing technology in the Turkish construction sector. This review covered multiple academic databases, including Scopus, ScienceDirect, and Web of Science, leading to the identification of 27 key drivers. The questionnaire consisted of two sections. The first section collected demographic information about the participants, while the second section listed the identified drivers, which respondents assessed using a 5-point Likert scale. The questionnaire was designed using Google Forms. Following its creation, a pilot study was carried out to verify the appropriateness of the questionnaire. Based on feedback from the pilot study participants, necessary adjustments were made to refine the questionnaire. After these modifications, the final version was prepared for distribution.

Data Collection

The target group included professionals from the construction sector working in both public and private organizations. The questionnaire was disseminated via email, providing a link to the online survey. A total of 107 responses were received; however, one incomplete response was excluded, leaving 106 valid responses for analysis.

Data Analysis

This study employs the Relative Importance Index (RII) method to evaluate the significance of drivers influencing the adoption of 3D printing technology in the construction sector. The RII is calculated using the following equation:

$$\mathrm{RII}(\%)=\frac{\Sigma \mathrm{S}}{\mathrm{H} \times \mathrm{N}} \qquad (1)$$

where;

ΣS = the sum of each importance score multiplied by the number of corresponding responses

H = the maximum possible value (5 in this study)

N = the overall number of respondents (106 in this study)

Results

Demographic Information about Respondents

The demographic characteristics of the respondents revealed a diverse range of professional backgrounds, organizational affiliations, and levels of knowledge regarding 3D printing in construction. The majority of participants (72%) were employed in private sector organizations, while 28% worked in the public sector. In terms of job roles, the largest group comprised academic professionals (25%), followed by project managers (15%) and design engineers (14%). Regarding educational background, 39% of the respondents held a Master's degree (M.Sc.), 33% had a Bachelor's degree (B.Sc.), and 28% possessed a Ph.D. A substantial portion (42%) had 6 to 15 years of professional experience, while 32% reported 1 to 5 years, and 22% had 16 to 25 years of experience. Additionally, knowledge of 3D printing in construction varied among participants, with 59% reporting low knowledge, 30% having moderate knowledge, and 11% demonstrating high proficiency in the technology.

Significance of Drivers

Table 1 presents the RII values along with the ranking of the 27 identified drivers based on responses from all 106 participants. The top ranked driver was "D9-Faster construction", followed by "D5- Lower rate of site accidents and fatalities", and "D1- Reduction in material waste".

On the other hand, the lowest-ranked driver was "D20-Freedom in design due to less strict standards," followed by "D27- Mass-customization independent of economies of scale" and "D16-Lower supervision costs".

Table 1: Significance of Drivers

Rank	Drivers	Description	RII Value
1	D9	Faster construction	0.87735849
2	D5	Lower rate of site accidents and fatalities	0.86037736
3	D1	Reduction in material waste	0.8509434
4	D6	Higher buildings energy efficiency due to improved insulation	0.8490566
5	D8	Rapid prototype fabrication	0.8490566
6	D13	Lower labor costs	0.84716981
7	D18	Easier and faster implementation of complex geometries	0.83962264
8	D17	Lower indirect cost due to faster construction	0.83396226
9	D26	Higher construction quality	0.82830189
10	D12	Lower material costs	0.80566038
11	D22	Direct design-to-print from virtual models (e.g., BIM)	0.80566038
12	D2	Greater customization and personalization with diverse materials	0.80377358
13	D4	Improved sustainability due to material options (e.g., metal, foam, geopolymer)	0.79811321
14	D15	Lower material transportation costs	0.79433962
15	D14	Lower material storage costs	0.79245283
16	D21	Higher flexibility to modify the design	0.79245283
17	D10	Productivity unaffected by weather conditions	0.79056604
18	D7	Less noise pollution	0.78113208
19	D3	Lower emissions due to the reduced materials and equipment requirements	0.77735849
20	D11	Simpler coordination with fewer parties (i.e., suppliers, contractor, subcontractors)	0.77358491
21	D19	Lower self-weight of structure due to smaller elements	0.77358491
22	D24	Improved supply chain efficiency due to on-demand production	0.76792453
23	D23	High-tech environment contributes to up-skilled, talented, and creative labor	0.76603774
24	D25	More efficient restoration and/or repairing of the existing facilities	0.76415094
25	D16	Lower supervision costs	0.76226415
26	D27	Mass-customization independent of economies of scale	0.76037736
27	D20	Freedom in design due to less strict standards	0.75283019

Discussion

According to the results, “D9-Faster construction” was perceived as the most important driver. Declining productivity and a growing shortage of skilled labor have presented major challenges to the construction industry (Hassan et al., 2024; Mechtcherine et al., 2019). While labor shortages and rising costs have driven the adoption of automation and digital construction technologies worldwide (Mechtcherine et al., 2019), Türkiye faces an even more pressing situation due to rapid urbanization. The construction sector is a key contributor to the national economy, accounting for 6.6% of real Gross Domestic Product (GDP) growth**,** with an urbanization rate of 2% per year, leading to a 4% annual increase in new construction (Copenhagen Centre on Energy Efficiency, 2018). This high demand for housing and infrastructure necessitates faster and more efficient construction methods**.** In this context, 3D printing technology offers a crucial opportunity for accelerating construction while maintaining quality and cost-efficiency.

The second most important driver is “Lower rate of site accidents and fatalities” With a persistently low safety record worldwide, the construction industry continues to be one of the most hazardous sectors (Al-Kasasbeh et al., 2021; Singh and Misra, 2021). Türkiye records the highest incidence of fatal work-related accidents among EU nations, with a rate of 5.7 fatalities per 100,000 individuals, which is almost three times the average for the EU (1.76). (Isik and Isikhan, 2024). The situation is particularly severe in the construction sector, where occupational fatalities accounted for 27.8% of all work-related deaths (Isik and Isikhan, 2024). Given these alarming figures, automating construction processes through 3D printing can help reduce human involvement in high-risk tasks, significantly improving site safety (Ali et al., 2022). Therefore, the potential to reduce accident rates and fatalities is perceived as a crucial driver for improving safety standards in construction projects.

The third most important driver was “D1- Reduction in material waste” The construction industry has consistently been a major contributor to waste generation (Perkins and Skitmore, 2015). Traditional methods often involve considerable on-site material waste due to inefficient measuring and cutting processes. (Bedarf et al., 2021). In Türkiye, this issue is particularly critical due to large-scale construction activities and high urbanization rates. For instance, Istanbul generates approximately 10,000 tons of waste daily, with each resident contributing around one kilogram of residential and construction waste per day (Esin and Cosgun, 2007). 3D printing, by contrast, minimizes material waste and supports a more sustainable, resource-efficient construction process (Tabassum and Mir, 2023). Hence, professionals in the Turkish construction sector view 3D printing as a promising approach for promoting sustainability.

The lower rankings of D16, D27, and D20 drivers stem from regulatory, economic, and industry-specific factors. A key issue is the absence of a dedicated design code, which limits the practical application of design flexibility. While globally, 3D printing enables greater freedom in architectural and structural design (Al-Raqeb and Ghaffar, 2024), the lack of standardized guidelines in Türkiye restricts its usability. Without official codes, industry professionals may hesitate to embrace the technology due to compliance, safety, and long-term viability concerns. The distinction between ‘D21-Higher flexibility to modify the design’ and ‘D20-Freedom in design due to less strict standards’ highlights an important industry preference. The higher ranking of design flexibility suggests that adaptability and real-time modifications during construction are more valuable than merely having fewer regulatory constraints. While relaxed design standards may offer creative freedom, industry professionals prioritize practical flexibility that allows adjustments during execution. D20, being ranked the least important can also be attributed to the uncertainty in constructability associated with freeform designs (Lavikka et al., 2018), which can diminish the practical value of increased design freedom in real-world applications. Additionally, while mass-customization is a known advantage of 3D printing (Tabassum and Ahmad Mir, 2023; De Rubeis et al., 2024), its economic benefits remain unproven in Turkish construction sector, which relies on economies of scale through standardized designs and bulk production.

The unique and varied nature of building projects, on the other hand, can complicate the real-world adoption of construction robots (Pan and Pan, 2020). In this regard, the experts may have found that the individualized requirements of each project limit the feasibility of achieving true mass-customization, making it difficult to fully leverage the potential of 3D printing technology in construction. The stochastic nature of 3D printing unit costs (Walzer et al., 2024a; Walzer et al., 2024b) suggests that while economies of scale may be achievable in the long term, traditional methods – particularly for constructing simple geometries – remain more cost-effective (De Soto et al., 2018) due to lower material costs and established workflows. This may explain why experts ranked D27 lower, as uncertain 3D printing costs and reliance on low-cost traditional methods favored conventional approaches. Moreover, lower supervision costs, often referred to as a benefit of 3D printing (Raza et al., 2024), may not hold significant weight in Türkiye due to entrenched labor practices and regulatory requirements. Without streamlined digital workflows and automated compliance checks, manual supervision remains the norm, and reduced oversight may be seen as a challenge rather than a cost-saving measure.

Cultural and institutional inertia also play a role, as the construction sector favors proven methodologies over experimental technologies. Unlike some developed countries where flexible regulatory frameworks encourage innovation, Türkiye’s reliance on traditional procurement and contracting models (Akiner and Akiner. 2018) creates barriers to adopting novel methods like 3D printing. Furthermore, the distinction between “soft value” factors like design freedom and “hard realities” like cost efficiency shapes industry preferences. Given that cost-effectiveness and feasibility drive decision-making, attributes offering conceptual advantages such as increased design freedom may be deprioritized in favor of tangible benefits. These factors explain why certain drivers ranked lower in the study, reflecting the complex interplay of economic, regulatory, and cultural influences (Delgado et al., 2019) on 3D printing adoption in Türkiye.

Conclusion

This study explored the key factors driving the adoption of 3D printing technology in the Turkish construction industry. To achieve this, a questionnaire survey was developed, incorporating 27 drivers identified through a comprehensive literature review. Expert opinions were collected through the survey, and the results were analyzed using the Relative Importance Index (RII) method to assess the significance and priority of these drivers. The findings highlight faster construction as the most significant driver for adopting 3D printing technology in the Turkish construction industry. Given the industry's ongoing productivity challenges and skilled labor shortages, automation presents a critical solution. The second most significant driver was improved safety, as 3D printing can reduce accident rates and fatalities by limiting human exposure to hazardous tasks. Another key driver was the reduction of material waste as conventional construction methods often lead to inefficiencies in resource utilization. 3D printing offers a sustainable alternative by optimizing material consumption. However, its widespread adoption in Türkiye depends not only on technological advancements but also on strategic policy measures. Aligning incentives with national construction needs – through public-private partnerships and targeted funding – can provide the necessary support for a structured transition. Addressing Türkiye's shortage of a specialized workforce, on the other hand, requires government-university initiatives for targeted training and stronger industry-academia partnerships to align education with construction sector needs. This study also has some limitations. Although the sample size is considered sufficient, a larger sample could improve the accuracy of the results. Additionally, this study did not examine the relationships between drivers. Future research could address these gaps by employing a larger sample size and advanced methods to examine the interdependencies among the identified drivers.

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