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KEY DRIVERS AND BARRIERS INFLUENCING THE ADOPTION OF 3D PRINTING TECHNOLOGY IN THE TURKISH CONSTRUCTION INDUSTRY

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This is to certify that we have read the thesis "Key Drivers and Barriers Influencing the Adoption of 3D Printing Technology in the Turkish Construction Industry" by Leva Latifiilkhechi and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

KEY DRIVERS AND BARRIERS INFLUENCING THE ADOPTION OF 3D PRINTING TECHNOLOGY IN THE TURKISH CONSTRUCTION INDUSTRY

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This study explores the key factors influencing the adoption of 3D printing technology in the construction industry, with a focus on Türkiye. An extensive literature review was conducted to identify 27 drivers and 19 barriers, which were subsequently evaluated through a survey of 106 industry experts. The significance of these factors was assessed using the Relative Importance Index (RII), and further analyzed with the Analytic Hierarchy Process (AHP) to prioritize and determine their relative importance. It is discovered that although 3D printing offers benefits such as faster construction, reduced site accidents, improved energy efficiency, and ease in implementing complex designs, its adoption is hindered by challenges including the lack of regulations and building codes for 3D Concrete Printing (3DCP), limited knowledge of large-scale applications, and insufficient availability of insulating materials. The results highlight that reducing material waste and enabling greater customization are the most significant drivers for adopting 3D printing in construction, while the reduction in supervision costs was the least important. Conversely, cybersecurity risks, potential job losses, and the layered and rough surface of printed structures were identified as the most critical barriers. This research underscores the need to address these drivers and barriers through targeted strategies to enhance the integration of 3D printing technology in the construction industry.

Keywords: 3D Printing, Construction, Drivers, Barriers, Relative Importance Index, Analytic Hierarchy Process.

ÖZ

TÜRK İNŞAAT SEKTÖRÜNDE 3B BASKI TEKNOLOJİSİNİN BENİMSENMESİNİ ETKİLEYEN ANA ETKENLER VE ENGELLER

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Ocak 2025, 83 Sayfa

Bu çalışmada, Türk inşaat sektöründe 3B baskı teknolojisinin benimsenmesini etkileyen temel faktörler incelenmiştir. Bu doğrultuda, kapsamlı bir literatür taraması sonucunda 27 teşvik edici ve 19 engelleyici faktör belirlenmiş olup, bu faktörlerin değerlendirmesi 106 uzmandan oluşan bir anket çalışması ile yapılmıştır. Bu faktörlerin önemi, Göreceli Önem İndeksi (GÖİ) kullanılarak değerlendirilmiş ve ardından Analitik Hiyerarşi Prosesi (AHP) ile faktörlerin önem düzeyleri belirlenmiştir. 3B baskı teknolojisinin daha hızlı inşaat, iş kazalarının azalması, enerji verimliliğinin artması ve karmaşık tasarımların daha kolay uygulanması gibi avantajlar sunduğu görülse de, bu teknolojinin benimsenmesini engelleyen başlıca zorluklar arasında 3B Beton Baskı için yeterli düzenlemelerin ve yapı kodlarının eksikliği, büyük ölçekli uygulamalar konusunda sınırlı bilgi ve yalıtım malzemelerinin yetersizliği yer almaktadır. Araştırma sonuçları, malzeme israfını azaltma ve daha fazla özelleştirme imkânı sağlama gibi faktörlerin 3B baskının inşaat sektöründe benimsenmesinde en önemli etmen olduğunu, gözetim maliyetlerinin azaltılmasının ise en az önemli teşvik edici faktör olduğunu ortaya koymuştur. Diğer yandan, siber güvenlik riskleri, potansiyel iş kayıpları ve basılı yapıların katmanlı ve pürüzlü yüzeyleri, en kritik engeller olarak belirlenmiştir. Bu araştırma, 3B baskı teknolojisinin inşaat sektörüne entegrasyonunun artırılması için bu etmenlerin ve engellerin hedefe yönelik stratejilerle ele alınması gerektiğini vurgulamaktadır.

Anahtar Kelimeler: İnşaatta 3B Baskı, Etmenler, Engeller, Göreceli Önem Endeksi, Analitik Hiyerarşi Prosesi.

To my beloved husband…

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CHAPTER 1

INTRODUCTION

The construction industry has struggled for a long time with many problems that have seriously slowed down its productivity, leaving it far behind other fields like manufacturing [1]. As one of the least digitalized industries globally, construction has a deep-rooted culture resistant to change [2]. This reliance on manual processes complicates project management, making it more time-consuming and inefficient [3], [4]. Consequently, the inadequate adoption of digital technologies has led to ineffective cost management, project delays, subpar quality, poor decision-making, and insufficient productivity, health, and safety outcomes [5].

Recently, the urgency for the construction industry to embrace digitalization and enhance its technical capabilities has become increasingly clear, particularly in the context of labor shortages and the pressing need to deliver sustainable infrastructures [6, 7, 8, 9]. The industry's traditional practices are further strained by adverse environmental conditions, high workplace injury rates, and a lack of skilled labor, all of which underscore the need for innovative solutions [10].

Innovative technologies present a promising solution to these entrenched challenges. By integrating advanced technologies, construction companies can minimize material wastage, shorten construction times, and provide designers with unprecedented freedom in creating architectural designs [11]. These transformative innovations have the potential to revolutionize traditional construction methods, paving the way for a more efficient, sustainable, and innovative future for the industry.

3D printing also known as additive manufacturing (AM), is a computer-aided design method that constructs structures layer by layer directly from a 3D model [12]. Initially seen as just a tool for rapid prototyping, it has evolved into a comprehensive production method used across various manufacturing fields [13, 14, 15]. Early on, 3D printing was mainly utilized to evaluate, modify, and approve designs, serving as a quick way to prototype new products [16]. This technique works by translating digital data into physical objects, allowing entire products or their components to be constructed through printing [17]

While 3D printing has been utilized across various industries, its adoption in construction has surged notably since Behrokh Khoshnevis's creative work in 1998, which promised to revolutionize the construction industry through his pioneering contributions to additive manufacturing [18].

3D printing also presents additional drivers for its adoption, including lower emissions resulting from reduced transportation needs due to minimized material and equipment requirements [18 , 19], Reduction in noise pollution [12 , 20], Faster construction [21, 22, 23]. Furthermore, it has the potential to reduce labor intensity and promote environmental sustainability [24]. Despite these advantages, the adoption of new methods in the construction industry faces a range of challenges. Resistance toward the adoption of technological innovations within the industry [25, 26], a lack of understanding about the utilization of 3D printers for large-scale buildings [27], and the requirement for a specialized workforce capable of designing 3D objects and setting up the necessary equipment [28] represent significant hurdles that may prevent the widespread implementation of 3D printing in construction. Addressing these challenges is crucial for realizing the full potential of 3D printing technology in revolutionizing the construction sector and overcoming its traditional constraints.

While existing studies have identified various barriers and drivers, there is a notable gap in research specific to the Turkish construction industry. To address this, the present study undertook a comprehensive literature review, identifying 19 barriers and 27 drivers that impact the adoption of 3D printing technology within this sector. By discussing and evaluating these unique barriers and drivers, this paper aims to clarify the factors affecting technology adoption, ultimately helping to develop customized, effective strategies for the practical integration of 3D printing technology in Turkish construction projects.

The following chapters outline the structure of this thesis: Chapter 2 provides a history of 3D printing, focusing on its evolution into 3D concrete printing and covering essential materials and techniques with attention to sustainability. Chapter 3 presents the study’s methodology, including a literature review on the current and future state of 3D printing in construction, key barriers and drivers, and the specific research gap within Türkiye’s industry. Chapter 4 analyzes the findings on Türkiye-specific drivers and barriers, while Chapter 5 interprets these results and their implications. Finally, Chapter 6 summarizes key insights and proposes directions for future research.

CHAPTER 2

IN-DEPTH EXPLORATION OF 3D PRINTING

Due to rapid population growth and increasing construction costs, the need for efficient and affordable building methods has become critical. In 1983, Charles W. Hull introduced the concept of 3D printing by suggesting the use of UV light to harden tabletop coatings, which paved the way for the first 3D printing technology [23]. This innovation enabled the rapid, precise, and repeatable production of components with computer assistance, establishing Hull as the "father of 3D printing" [23]. In 1998, Behrokh Khoshnevis pioneered the use of additive manufacturing in construction, sparking a new era focused on developing construction materials, 3D printing setups, novel application methods, and unique structural designs [29]. A review by Tay et al. [30] highlights that until 2009, research in 3D printing for construction was relatively limited, but a surge in interest since then has led to a significant increase in published studies [31].

The pioneering efforts in printing the world's first 3D printed house were demonstrated by WinSun Company in China in 2014 (Fig. 2.1), which utilized a unique blend of materials including cement, glass fiber, and construction waste. In the same year, Andrey Rudenko, working for a Russian company, achieved a milestone by 3D printing a concrete castle in the US (Fig. 2.2) [11], [32]. However, the landscape evolved significantly post-2016, with various companies experimenting with diverse materials such as reinforced concrete, fiber-reinforced plastic, and glass-fiber reinforced gypsum in Dubai (Fig. 2.3) [18]. Moreover, Russian companies have made strides in printing individual houses using cement-based paste materials [33]. A notable development occurred in Türkiye in 2021, where a 3D-printed structure was successfully built, further highlighting the growing global interest and capabilities in this technology (Fig. 2.4) [34]. These advancements emphasis the variety of 3D printing in creating three-dimensional material structures.

Figure 2.1: The world’s first 3D printed house printed in 2014 in China (Photo courtesy of Karyne Levy).

Figure 2.2: The world’s first 3D printed castle printed in 2014 in The USA (Photo courtesy of Andrey Rudenko).

Figure 2.3: The world’s first 3D printed office printed in 2016 in Dubai (Photo courtesy of Leva Latifiilkhechi).

Figure 2.4: House printed in 2021 in Türkiye by İston Company (Photo courtesy of Saman Aminbakhsh).

This section immerses into significant trends in 3D printing technology as it pertains to the construction industry. It offers a detailed analysis of critical elements such as the variety of materials utilized in 3D printing, the range of techniques employed, the sustainability properties of these methods, and the challenges and risks they present.

2.1 Exploring Construction Materials for 3D Printing Applications

3D printing technology, also known as additive manufacturing, is transforming various industries, including construction. It offers the potential to create complex structures with enhanced precision and efficiency, using a variety of materials that must meet specific criteria to be effective in the construction process. Beyond traditional materials, such as cementitious compounds, polymers, and metals, alternative materials [10, 35] like wood, waste products, and recycled materials are also being explored for their potential in sustainable construction [36] These materials offer the possibility of reducing environmental impact while providing the necessary properties for structural integrity and durability [24].

2.1.1 Cementitious Materials

Cement-based materials are the most commonly used in construction 3D printing. This is largely due to their availability, affordability, and compatibility with large-scale construction. Cementitious materials, which include concrete and mortar, must be carefully formulated to ensure they are fluid enough for extrusion while also possessing sufficient strength to maintain the integrity of the printed structure once hardened. Studies have shown that achieving the correct balance of viscosity, setting time, and strength is critical for these materials to be successfully used in 3D printing [37].

2.1.2 Polymer Materials

Polymers are another class of materials employed in 3D printing, particularly in applications where flexibility, lightweight structures, or insulation properties are required. Thermoplastics, for example, can be heated and reshaped, making them ideal for additive manufacturing processes [38]. In construction, polymers are often used in conjunction with other materials to enhance specific properties, such as resistance to environmental factors or increased durability. The use of polymers also enables faster production times due to their rapid cooling and solidification rates after printing [39].

2.1.3 Metallic Materials

Although less common than cementitious materials or polymers, metals have also found their place in construction 3D printing, especially in applications requiring high strength and durability. Metallic materials like steel and titanium are increasingly used in specialized projects, such as the fabrication of structural components or fixtures within a building. The use of metal in 3D printing has been facilitated by advances in technologies like selective laser melting (SLM) and electron beam melting (EBM), which allow for the precise formation of metal parts layer by layer [40]. These materials provide significant strength and are used where traditional construction materials may not offer the necessary performance.

2.1.4 Essential Material Criteria for 3D Printing

For any material to be effectively used in 3D printing, it must meet specific criteria related to workability, strength, and environmental sustainability. Workability refers to the material's ability to be extruded or deposited in layers without causing interruptions to the printing process [41]. Additionally, the material must develop sufficient early strength to support subsequent layers, a challenge particularly relevant for vertical construction. Sustainability is also a key consideration, as many construction projects aim to reduce their environmental footprint by incorporating eco-friendly or recyclable materials [42].

2.2 Techniques

The most widely recognized additive manufacturing (AM) methods include Contour Crafting (CC) [43], concrete printing [44], and D-shape printing [45]. Additionally, innovative techniques such as selective binder activation, selective paste intrusion, and rock printing have been developed [46]. The early prototypes of concrete printing in additive manufacturing (AM) were based on similar principles to large-scale fused deposition modeling (FDM), utilizing a deposition head system mounted on a gantry [47]. Among the various additive manufacturing (AM) systems, FDM-based AM has been identified as using the most cost-effective materials [48]. additive manufacturing (AM) , a specialized form of 3D printing, is designed for large-scale construction applications. In this process, concrete is the primary material, and its printing operates similarly to inkjet printing, utilizing a pipe-pump-nozzle system [12].

2.2.1 Contour Crafting

Contour Crafting (CC) is an additive manufacturing (AM) technique that uses cement-based paste materials for construction [49]. This process is recognized for producing higher surface quality compared to other additive manufacturing (AM) methods. It was first introduced in 1998 by Khoshnevis et al. at the University of Southern California as part of a groundbreaking project [29]. The CC system employs a gantry setup, which enables movement along the x, y, and z axes of the Cartesian coordinate system. Later developments in CC involved an extrusion system for materials like spackling compounds and clay, where a piston, a raw material-carrying cylinder, and a threaded feed rod work together to push the material through the nozzle [36, 50] , One of the standout features of this technology is the smooth surface finish, achieved with the help of trowels mounted on the extrusion system [51]. The printer typically has a resolution of about 13mm [12].

Further research focused on the use of sulfur concrete in the CC process, particularly how temperature variations in the extruder, sulfur content, and extrusion rate influenced the surface quality of the printed material [43]. The results showed that sulfur content and temperature had a notable impact on the quality of the extruded surfaces, with experimental data aligning closely with finite element analysis. Sulfur concrete was found to be particularly suitable for use in space construction applications. Zhang and Khoshnevis later suggested an optimized approach to CC, aimed at effectively building large-scale, complex structures [52]. This included the possibility of creating dome-shaped structures without the need for external supports or molds. Additionally, their research examined the bonding strength between layers in the CC process. The findings revealed that several factors, such as the type of cementitious material, water-to-cement ratio, fiber content, and chemical admixtures, significantly affected the adhesion between layers, emphasizing the need to carefully select materials to enhance bonding strength [53, 12].

Figure 2.5: Contour crafting Machine (Photo courtesy of Sagheer A. Ranjha).

2.2.2 Concrete Printing

Since 2007, research teams at Loughborough University in the UK, together with Skanska, have worked on developing a 3D concrete printing system. This system integrates a robotic arm and gantry to move additive manufacturing (AM) toward commercial viability [22]. At this stage, however, the available inking materials for this technology are somewhat limited. The materials currently used in 3D concrete printing include cementitious substances such as clay, Portland cement, gypsum, dry mortar, fly ash, and sand. Researchers continue to explore the best possible combinations and proportions of these materials to optimize their performance in both academic and industrial contexts [12].

One example of progress in this area comes from a study by Ding et al. [54], who incorporated hydroxypropyl methylcellulose into sulphoaluminate cement, significantly boosting the compressive strength of the extruded mortar [12]. The 3D printing process, referred to as freeform construction, is similar to extrusion systems like fused deposition modeling (FDM) and offers better control over geometries and a higher resolution than Contour Crafting (CC), ranging from 4 to 6mm. A secondary support material is often required, with post-processing steps, such as removing these supports, also being necessary [12].

Selecting the appropriate aggregate particle size is crucial for preventing issues such as nozzle blockages, while small particle sizes can elevate the hydration heat of the cement. Thus, choosing the right aggregate size depends largely on the nozzle's dimensions [12]. In a case study by Prasittisopin et al. [55], the design and construction of a curvilinear self-supporting pavilion were investigated, highlighting both the current limitations and the advantages of 3D printing technology for construction purposes.

Another study explored the use of polymer concrete in large-scale 3D printing. The findings revealed that the mechanical properties of 3D-printed parts were nearly equivalent to cast parts, although there were differences in failure patterns, with the printed parts showing higher porosity [56].

Ur Rehman and Sglavo [57] studied the effect of binder flow rates on the dimensional accuracy of 3D-printed parts, using water-based binder formulations compatible with Portland cement. Rushing et al. [58] also investigated conventional concrete mixtures, finding that high amounts of coarse aggregate often lead to nozzle clogs in AM. However, mixtures with reduced coarse aggregates performed better, suggesting that conventional materials could be adapted for additive manufacturing (AM). This adaptation could lower costs and make AC more accessible on a global scale [58].

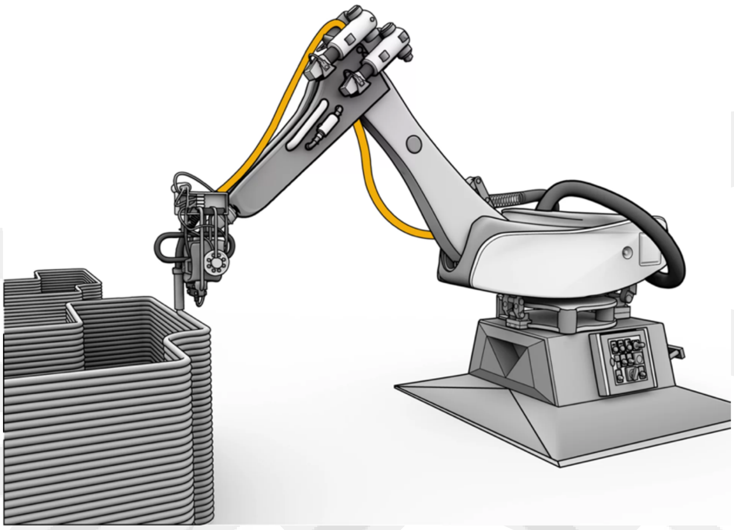

Figure 2.6: Concrete printing Machine (Photo courtesy of Sika Building group).

2.2.3 D-Shape Printing

D-shape printing is recognized as a prominent additive manufacturing (AM) method that offers an alternative approach to concrete printing. This technique utilizes powder-based materials along with binder jetting systems [59]. Liquid adhesives are selectively deposited onto layers of cement powder, with the process repeating until the entire object is formed. The application of the binder causes specific areas of the powder to solidify, resulting in strong bonds between the powder particles. Subsequently, cleaning of the powder support is required. The printer operates with an accuracy range of 10–20mm. Two primary input materials are needed: a liquid binder and dry powder, with magnesium oxide and magnesium chloride commonly used as binders [10].

A study conducted by Cesaretti et al. [60] successfully demonstrated the application of D-shape printing in creating full-scale building components from lunar soil. This technology is anticipated to enable the military to construct infrastructures, such as bases and hospitals, at a significantly faster pace compared to conventional methods. A notable advantage of this system is its elimination of the need for support structures during printing; the unbonded powder itself serves as a supportive framework for the printed structure [61].

Additionally, D-shape printing allows for a wide selection of materials, utilizing any sand-like substances without generating waste, as excess material can be reused in subsequent construction projects. The final printed structures exhibit a natural stone-like appearance due to minimal preprocessing required at the start of the printing process [62]. However, challenges such as difficulties in cleaning and in-situ printing are associated with powder printing [63].

Figure 2.7: D-Shape printing Machine (Photo courtesy of Adlughmin).

2.2.4 A Comparative Overview of 3D Printing Techniques in Construction

Three primary 3D printing techniques are emerging as significant players in the construction industry: Contour Crafting, Concrete 3D Printing, and D-Shape. Each method offers unique advantages and limitations, making them suitable for different applications A detailed comparison of these techniques is provided in Table 2.1. This comparative overview explores the key differences between these techniques, examining their processes, capabilities, and potential impact on the future of construction [36].

Table 2.1: Comparison of 3D Printing Techniques in Construction

Feature	**Contour Crafting** [36]	**Concrete 3D Printing** [49]	**D-Shape** [59]
Process	Extrusion of continuous layers	Robotic deposition of concrete	Spraying of cement-based slurry
Shape Complexity	Limited to consistent cross-sections	More complex shapes possible	Highly complex shapes possible
Speed	Relatively fast for simple structures	Slower for complex structures	Can be slow for large-scale structures
Labor Requirements	Lower labor requirements	Higher labor requirements	High labor requirements for setup and support structures

2.2.5 Robotic Technologies in Construction 3D Printing Techniques

Recent developments in large-scale 3D printing technology have made significant strides, allowing for the construction of industrial-scale buildings. Two prevalent delivery methods in 3D-printed construction are gantry systems and articulated robot systems. The gantry system operates based on a Cartesian coordinate system, where the printer nozzle moves across three axes (X, Y, Z) [64]. Although this method offers advantages, it faces challenges such as transportation, installation, and overall size limitations [33].

The gantry system includes additional movement around the z-axis, enabling the nozzle to maintain tangency to the tool path during direction changes. However, this design can hinder the ability to create sharp corners in concrete structures due to the need for gradual nozzle movement to avoid twisting the filament [65]. Moreover, robotic systems themselves have inherent limitations; for instance, achieving sharp corners may lead to acceleration challenges and the risk of excessive oscillation, negatively impacting print quality.

Articulated robot systems, comprising robotic arms, can be mounted on transportable platforms, thereby requiring less space than gantry systems. However, the workspace for articulated robots is typically more restricted. The design of these robots often limits their reach and can create difficulties in achieving sharp corners or complex shapes [10]. Despite these limitations, teams of mobile robots have been proposed to collaborate in creating large structures, thereby expanding the possibilities of 3D printing [66].

Additionally, innovative designs like the cable robot have emerged, which offer advantages in terms of cost, weight, and ease of transport. These robots can also experience workspace limitations due to cable interference [67]. Nevertheless, cable-suspended robots demonstrate an increased degree of freedom (DOF) and can produce complex geometries while maintaining a more manageable workspace.

Robotic manipulators also play a crucial role in advancing automated construction processes. For example, eco-friendly mobile robot systems developed by Batiprint3D significantly enhance working conditions by reducing environmental costs and improving execution quality. These systems utilize polymer materials to create insulation layers around concrete structures, although the printed layers may not achieve a smooth finish and require additional protection [68].

Furthermore, platforms like the ATHLETE robotic system demonstrate the potential for performing complex tasks in hazardous environments, showcasing versatility in construction applications [69]. Collaborations between academic institutions and industry leaders have led to projects where drones autonomously assemble architectural installations, underscoring the potential of robotics to reshape traditional construction practices [70] .

2.2.6 Sustainability Property Aspects

Sustainability is characterized by the aim to conduct activities that fulfill present needs while safeguarding the ability of future generations to meet their own needs [71] . The

Leadership in Energy and Environmental Design (LEED) rating system is a recognized framework for assessing sustainability levels in construction projects [72].

The global population continues to grow, leading to the overexploitation of natural resources. As noted by Abrar Malik et al. [73], the establishment of more industries to meet the needs of this rising population further contributes to the depletion of these resources. Recognizing the limitations of natural resources underscores the importance of sustainability, which emphasizes the responsible use of resources to ensure that future generations are not deprived [74]. As a result, quantifying sustainability is essential for engineers and practitioners undertaking sustainable activities.

Implementing 3D printing technology in the construction sector promotes sustainability and economic efficiency [75, 76]. A significant advantage of 3D printing over conventional construction methods is the substantial reduction of material waste. Sustainable development has emerged as a critical area of research, focusing on three pillars: social, economic, and environmental sustainability. For example, a 3D-printed house in Denmark utilized a concrete mix incorporating recycled materials, such as tiles, while its walls were insulated with recycled cellulose fiber [77]. Moreover, 3D printing is viewed as a more efficient and environmentally friendly approach to manufacturing, particularly when dealing with complex designs [78].

Research by Perrot et al. [79] examined the feasibility of employing earth materials in 3D printing. Their findings indicated that incorporating alginate into the earth materials led to high productivity levels, with compressive strength comparable to traditional earth construction [79]. Geopolymers also demonstrate significant sustainability benefits. A study by Zhang et al. [80] evaluated the advantages and energy-saving potential of geopolymer foam concrete, highlighting its low cost and favorable strength-to-weight ratio.

Additionally, researchers have explored contour crafting technology and its implications for sustainable construction, recommending 3D printing as the future of this sector [46]. Innovations in building information modeling (BIM) have also integrated 3D printing techniques to enhance efficiency and sustainability [81]. The potential of utilizing plastic waste as raw material for 3D printing presents an opportunity to address the growing concern of ocean pollution from plastic debris. Researchers have proposed prototypes that convert collected plastic waste into filaments for 3D printing, contributing to a circular economy [82].

Furthermore, scientists argue that 3D printing facilitates distributed production and encourages the use of renewable energy sources [30]. This method significantly reduces material waste compared to traditional subtractive manufacturing processes, which involve various energy-intensive techniques such as cutting, drilling, and milling. As a result, 3D printing is becoming increasingly sustainable, with researchers indicating that the energy impacts of 3D-printed objects must be carefully considered alongside the environmental benefits [83].

Overall, the incorporation of 3D printing technology in construction not only aligns with sustainability principles but also presents numerous advantages, including social benefits, safer construction sites, reduced formwork, minimized waste, and eco-friendly structures [64].

Building on this foundation, the next chapter delves into the challenges and drivers shaping the evolution of 3D printing in construction. It offers a comprehensive overview of the current status of 3D printing technology in construction and forecasts its future trajectory, identifying both ongoing and emergent challenges and potential risks associated with its adoption and development.

CHAPTER 3

LITERATURE REVIEW

Various studies examining the barriers and drivers of implementing 3D printing in construction, conducted through literature reviews, have highlighted worldwide developments. Countries such as China [35], Singapore, and the United Arab Emirates have shown significant interest in 3D printing, with substantial research efforts dedicated to the field. Similarly, the United States and Australia have emerged as competitive players in the development of 3D-printed buildings, showing notable achievements [84].

The construction sector is recognized as a significant contributor to economic profitability and serves as a foundational pillar within the comprehensive industrial context [85]. However, the industry's historical reliance on manual labor is increasingly perceived as inefficient in the context of contemporary technological advancements [86]. The development and implementation of technology in the construction industry have the potential to make traditional manual labor and hand trades less efficient, as these methods are generally more time-consuming and costly [23]. Additionally, traditional construction methods also face safety and environmental challenges, such as those posed by extreme conditions in polar and desert regions, risks of chemical contamination, and the particular demands of off-world applications, which necessitate increased attention for the future [65]. The integration of advanced technologies stands to significantly simplify processes, reduce expenses, and reinforce overall productivity [87]. This contrast between traditional labor-intensive practices and innovative technological applications emphasizes the pressing need for the construction industry to embrace change [88]. To maintain its competitive edge and satisfy the dynamic demands of the market, the industry must evolve beyond its conventional practices through the adoption of technological innovations [65]. Process automation marks a substantial shift from traditional construction methods, playing a pivotal role in redefining the industry [89]. These improvements are particularly crucial in the context of developing affordable housing. Furthermore, the adoption of 3D printing technology is especially beneficial, providing increased design freedom. This enables the production of elements with complex geometries, which are in harmony with the futuristic vision that characterizes modern architecture (Fig. 3.1) [90].

Figure 3.1: House printed houses in 2022 in Italy (Photo courtesy of Sarah Amelar).

3.1 Drivers of 3D Printing in Construction

Traditional construction methods are known for high material wastage, contributing significantly to pollution and the excessive use of resources [86]. In contrast, additive manufacturing, or 3D printing, minimizes material usage [91] and, because it does not require molds, enables faster and more precise formation of components, resulting in lighter finished products [83].

Consequently, the reduced material use in 3D printing can lower building construction costs [75], and offers several advantages over conventional methods [83]. These include less material and energy consumption [23, 92] and reduced demand for labor.

Safety issues are prevalent in the construction industry [93] , but Perkins and Skitmore [61] argue that 3D printing can enhance workplace safety, as most tasks are automated and require minimal supervision [83]. Additionally, 3D printing’s automation allows for remote operation in challenging conditions [94]. This technology supports streamlined design and development, helping clients achieve their goals efficiently [88]. and providing flexibility for complex designs and quick correction [88].

3D printing can adapt to various environmental conditions in on-site construction [95] and can also integrate recyclable materials, promoting sustainability [35] . By reducing the need for multiple suppliers and transportation, 3D printing helps decrease logistics costs due to its efficient use of construction materials [96]. Although most 3D printing projects are still managed in controlled environments like labs [86] , long-term cost-benefit analyses suggest that 3D printing can save over 50% compared to traditional methods [86]. Research by Ali et al. [12] highlights substantial waste reduction with 3D printing.

This technology brings value to the construction industry by enabling the production of high-quality, multipurpose building components without formwork [61], [97] especially for intricate geometries that optimize material use. Le et al. [31] discuss the development of high-performance concrete specifically for 3D printing architectural and structural components without formwork, which is also applied in building renovations and infrastructure repairs [83].

For 3D printing to advance in construction, there is a need for skilled, innovative professionals who can design objects, configure digital materials, set up equipment, and utilize specialized software [98]. Environmental concerns, such as noise and pollution, can also be mitigated with this technology, and the digital nature of 3D printing offers the potential for relocating projects and enhancing the precision of constructed parts [99].

3.2 Barriers of 3D Printing in Construction

While 3D printing offers numerous benefits to the construction industry, it also introduces a range of limitations and challenges that impact its broader adoption and functionality.

One prominent material-related issue is layer deformation, which can occur during the rapid extrusion process, resulting in defects in the printed structure [100]. Mitigating these imperfections requires real-time quality control and corrective measures. Additionally, large-scale 3D printing presents logistical difficulties, particularly when transporting lab-produced components to construction sites [75]. During transit, materials are susceptible to deformation, which can compromise their integrity and suitability for on-site application [101]. Another challenge is achieving smooth and even surfaces [20], this limitation discourages many from embracing 3D printing technology, as effective solutions for enhancing surface quality are still limited [71].

Supply chain demands and logistical obstacles further complicate the adoption of 3D printing [12]. Client involvement in the design phase can create additional time constraints, adding complexity for engineers and impacting project timelines [93] The lack of specialized equipment for large-scale 3D printing also restricts the size of structures that can be printed, while limitations in material extrusion hinder the ability to create complex angles, cantilevers, and free-form designs [27 ,101]. Moreover, uncertainties surrounding product performance, coupled with challenges in meeting standardization and building code compliance, continue to hinder the technology's adoption [102] , Managing the risks, influential factors, and technical intricacies of operating robots and advanced machinery also introduces a layer of complexity to project management [87].

The logistical requirements of setting up, transporting, and assembling large 3D printers at construction sites further limit the technology's flexibility and mobility [103, 97]. Technological barriers, such as installation and operation difficulties, remain prevalent as engineers and workers encounter integration challenges in adapting 3D printing to conventional construction workflows[26, 28].

Another significant barrier to 3D printing in construction is the hesitancy or outright resistance from clients and industry stakeholders. Many are reluctant to adopt new technologies, perceiving them as complex or unfavorable, with particular resistance observed among government agencies and labor groups who fear job displacement [104]. Intellectual property risks, especially theft of digital design files, also pose a unique challenge for 3D printing in construction, as digital files defining a building's structure can be copied and resold without authorization [23].

Financial barriers, including the high initial investment needed for 3D printing equipment, represent yet another hurdle [97, 105, 106]. The technology is also constrained by physical limitations, which make mass production difficult, and by the mechanical properties of 3D-printed materials, which often do not match those of traditional construction materials, raising concerns about structural durability [105]. The risk of design model or printing setting errors is also substantial, as such issues can lead to accidents or financial losses if left unchecked [23].

Additional technical barriers include inadequate research on insulation methods, as traditional building materials typically offer better thermal resistance than current 3D-printed alternatives [107]. While some solutions, like foam inserts, have been explored, issues around the release of potentially harmful compounds during the printing process remain, with unclear implications for human health and the environment [20]. Finally, 3D-printed structures often require reinforcement to ensure resilience, particularly in earthquake-prone regions, underscoring the need for enhanced structural stability in future designs [106].

3.3 Current and Future State

Current research in 3D printing for construction largely focuses on optimizing materials and printing processes to support various scales and environmental conditions [108, 109]. Despite these advancements, however, large-scale applications of additive manufacturing (AM) in construction remain limited. A significant research gap still exists between controlled laboratory experiments and practical, real-world applications. Noteworthy implementations, such as the 3D printing of historical building components or concrete road repair, underscore AM’s potential in the construction industry [110, 111]. Projects like NASA’s exploration of AM for space construction further highlight the technology’s expansive future applications [112].

Despite its promise, several challenges and risks continue to impede the broader adoption of 3D printing in construction. Material and equipment issues are among the foremost obstacles; materials for large-scale projects must exhibit high flowability and rapid setting times. Often, results achieved in laboratory-scale tests do not effectively translate to larger applications, due to variables like printing scale, filament dimensions, and the pumping distances required for material delivery [41, 113]. In terms of technology, the accuracy of large-scale 3D printing systems can be affected by mechanical deformations in components such as robotic arms. Progress in areas like motion compensation, real-time data feedback, and process simulation is necessary to address these technical limitations [24]. Additionally, regulatory barriers pose significant challenges, as building codes and safety standards are still adapting to accommodate 3D printing technologies. The slow pace of regulatory adaptation hinders wider adoption of AM within the industry [71].

Economic factors also play a critical role in the adoption of 3D printing for construction. While 3D printing offers potential cost savings in certain areas, it remains expensive in its developmental phases. Zuo et al. (2021) emphasize the financial risks associated with printing full-scale buildings without extensive testing; errors in design or printing parameters can lead to substantial financial losses [114].

Although numerous studies have explored the barriers, drivers, and general landscape of 3D printing worldwide, there remains a significant research gap focused on the Turkish construction industry. This study aims to address that gap by conducting a comprehensive literature review to identify the specific barriers and drivers affecting 3D printing adoption in Türkiye. By investigating these unique factors, this paper seeks to clarify the challenges and motivators shaping the integration of 3D printing, ultimately aiming to develop practical, targeted strategies for the successful implementation of 3D printing technology in Turkish construction projects.

CHAPTER 4

METHODOLOGY

In this study, the focus is placed on identifying and analyzing the key barriers and drivers that directly affect the implementation of 3D printing technology in the Turkish construction industry. The research methodology is structured in stages, as illustrated in Figure 4.1. These stages include ‘questionnaire development,’ ‘data collection,’ ‘data analysis,’ and ‘presentation of results,’ each of which will be elaborated upon in the following sections of this study.

Figure 4.1: Research methodology

4.1 Questionnaire Design

In this study, the development of the questionnaire involved two main phases: a thorough literature review followed by a pilot study. The initial phase began with an extensive review of existing literature to identify both drivers and barriers to the adoption of 3D printing technology in the Turkish construction sector. This review spanned several sources, including Scopus, ScienceDirect, and Web of Science, covering studies from 1989 to the present, with a particular focus on publications from 2010 to 2024. As a result, 27 key drivers and 19 significant barriers were identified, which are presented in Tables 4.1.and 4.2, along with relevant references for further exploration. These identified factors served as the foundation for the questionnaire, which was subsequently distributed among industry professionals to collect their insights and perspectives.

A quantitative approach was adopted, with a two-part questionnaire consisting of closed-ended questions. The first part gathered demographic and general information from the respondents, while the second part asked them to evaluate the significance of the 27 drivers and the severity of the 19 barriers. Both drivers and barriers were rated on a 5-point Likert scale, where the scale for drivers ranged from ‘Not at all important’ to ‘Extremely important’, and for barriers, it ranged from 1 (Not at all important) to 5 (Extremely important).

Before full implementation, the questionnaire underwent a pilot study involving six experts, comprising both academics and experienced practitioners, to assess its suitability and comprehensiveness. Their feedback was carefully analyzed, leading to minor revisions aimed at improving clarity and ensuring the questionnaire was robust and effective.

Table 4.1: Drivers of adoption of 3D printing in Turkish construction industry

Drivers	Description	Reference(s)
D1	Reduction in material waste	[12], [23], [30], [61], [78], [88], [115], [116], [117]
D2	The ability to have more customization and personalization in manufacturing with the use of diverse materials.	[88], [118]
D3	Lower emissions from transportation due to the reduced materials and equipment requirements	[75], [88], [96], [119]
D4	The ability to use materials such as metal, foam, geopolymer, etc. helps improve sustainability of buildings.	[88], [92], [108], [115]
D5	Lower site accidents and fatalities	[12], [61], [75], [96], [97], [115]
D6	Higher energy efficiency in the buildings due to improved insulation	[92]
D7	Reduction in noise pollution	[12]
D8	Fast fabrication of the prototype	[120]
D9	Faster construction	[23], [30], [61], [75], [92]
D10	Productivity unaffected by the changing weather conditions	[30], [95], [96]
D11	Involvement of fewer parties (i.e., suppliers, contractor, subcontractors) makes coordination simpler	[115]
D12	Lower material cost	[75]
D13	Lower labor cost	[61], [115]
D14	Lower material storage cost	[75]
D15	Lower material transportation cost	[75], [88], [101]
D16	Lower supervision cost	[71]
D17	Lower indirect cost due to faster construction	[23], [88]
D18	Enables implementing complex geometries easier and faster	[41], [88], [101], [115]
D19	Lower self-weight of the structure due to smaller structural elements	[12], [101]
D20	Freedom in design due to limited standards and building codes	[95]
D21	Higher flexibility to modify the design	[88], [92]
D22	Enables direct transfer of design from a virtual environment (e.g., BIM) to the 3D printer	[121]
D23	High-tech environment contributes to upskilled, talented, and creative labor resources	[87]
D24	Improved supply chain efficiency due to on-demand production	[88], [96]
D25	More efficient restoration and/or repairing of the existing facilities	[87], [88]
D26	Higher quality of construction	[12], [61], [96]
D27	3D printing enables mass-customization regardless of economies of scale	[88]

Table 4.2: Barriers to adoption of 3D printing in Turkish construction industry

Barrier	Description	Reference(s)
B1	Lack of knowledge about sustainability of 3D printing materials	[11], [87], [122]
B2	Limited availability of insulating materials	[101], [106]
B3	Possibility of negative impact on human health due to potentially harmful new substances	[108]
B4	Significant startup costs associated with this technology	[10], [25], [30], [105], [106]
B5	Transportation of large 3D printers can be challenging and costly	[10], [18], [71], [110], [119], [123], [124]
B6	High costs associated with the concrete used in 3D printing	[125]
B7	Layered and rough surface of the printed structures	[20], [75]
B8	Lack of knowledge about mechanical properties of the printed structures	[120]
B9	Reinforcement of concrete can be challenging	[64], [106], [110]
B10	Current technology is not ready for printing large-scale buildings	[11], [30], [48], [75], [110], [111], [126]
B11	Lack of government regulations, standardizations, and building codes on 3D Concrete Printing (3DCP)	[12], [108], [115], [127]
B12	Complexity and risks associated with adoption of 3D printing technology in construction industry	[18], [75], [115]
B13	Cybersecurity risks associated with 3D printing	[23]
B14	Lack of knowledge about the usage of 3D printers for large-scale buildings	[27]
B15	Errors in design and/or mistakes in printer settings can easily lead to losses, waste, and rework	[18], [24]
B16	Leads to job losses and difficulties securing employment	[30], [75], [113], [127]
B17	Requires specialized workforce for designing 3D objects and setting up the equipment	[28]
B18	Resistance towards adoption of technological innovation by the industry	[25], [26]
B19	Lack of knowledge about buildability and/or workability of 3D printing materials	[11], [24], [25], [30], [48], [75], [98], [101], [108], [115]

4.2 Data Collection

In this study, the selection of appropriate respondents was key to ensuring the accuracy and relevance of the data collected. The target group included professionals from the construction sector across both public and private organizations. The survey gathered detailed demographic information, including respondents’ job roles, professional titles, years of experience, and educational backgrounds. Additional questions covered the type, size, age, and major field of activity of their organizations, as well as the respondents' level of knowledge in 3D printing technology.

The questionnaires were disseminated via email, containing a link to an online survey. Out of the 107 responses received, one was incomplete and excluded, leaving 106 valid responses for analysis. These responses provided valuable insights into both the drivers and barriers to the adoption of 3D printing technology, which were then analyzed in alignment with the study's objectives.

Table 4.3 presents the categorized drivers, and Table 4.4 presents the categorized barriers. The factors were categorized based on their meanings, with closely related factors grouped into the same category to ensure a structured and coherent analysis.

Table 4.3: Drivers categorized

Environment	Time	Cost	Design	Technology
D1	D8	D12	D18	D23
D2	D9	D13	D19	D24
D3	D10	D14	D20	D25
D4	D11	D15	D21	D26
D5		D16	D22	D27
D6		D17		
D7				

Table 4.4: Barriers categorized

Environment	Cost	Quality	Government	Risk and Uncertainties	Technology	People
B1	B4	B7	B10	B12	B14	B17
B2	B5	B8	B11	B13	B15	B18
B3	B6	B9			B16	B19

4.3 Data analysis

This study aims to create a quantitative framework that reflects the views of industry experts. Specifically, construction professionals were asked to assess the importance of several factors using a 5-point Likert scale, as outlined in Table 4.5.

Table 4.5: Scale for Assessing the Impact of Each Drivers and Barriers

Score	**1**	**2**	**3**	**4**	**5**
Level of significance	Not at all Important		↔	Extremely important	

After the factors were evaluated using the scale in Table 4.5, participants were presented with questions such as "D1 - Reduction in material waste" and "D12 - Lower material cost." Their responses were recorded according to the importance scale outlined in Table 4.6, providing essential insights into the drivers influencing the adoption of 3D printing technology.

Table 4.6: Response Counts for Each Importance Rating of Drivers

Drivers	1	**2**	**3**	**4**	**5**	**Total**
		↔	**Importance score**		↔	
D1	2	5	12	32	55	106
D2	3	4	24	32	43	106
D3	4	7	20	41	34	106
D4	4	3	19	44	36	106
D5	1	6	15	22	62	106
D6	1	6	11	36	52	106
D7	2	6	27	33	37	105
D8	2	4	17	26	57	106
D9	2	4	9	27	64	106
D10	3	7	23	32	41	106
D11	4	5	23	43	31	106
D12	4	7	16	34	45	106
D13	3	3	14	32	54	106
D14	3	9	18	35	41	106
D15	3	7	22	32	42	106
D16	3	12	22	34	35	106
D17	3	3	14	39	47	106
D18	2	0	16	45	43	106
D19	7	2	22	42	33	106
D20	3	9	24	44	26	106

Table 4.6 (cont'd)

D21	3	5	20	43	35	106
D22	5	4	16	39	42	106
D23	2	9	26	37	32	106
D24	4	4	26	43	29	106
D25	3	6	26	43	28	106
D26	3	3	15	40	45	106
D27	3	6	24	49	24	106

In addition to the drivers, participants also addressed barriers such as "B1 - Lack of knowledge about the sustainability of 3D printing materials" and "B19 - Lack of knowledge about buildability and/or workability of 3D printing materials." These assessments are summarized in Table 4.7, aiming to identify the factors that may hinder the adoption of 3D printing technology in the construction industry.

Table 4.7: Response Counts for Each Importance Rating of Barriers

Barriers	1	**2**	**3**	**4**	**5**	**Total**
	↔		**Importance score**		↔	
B1	2	6	22	36	40	106
B2	3	6	33	39	25	106
B3	6	19	24	26	31	106
B4	3	2	22	33	46	106
B5	4	13	26	22	41	106
B6	5	6	22	35	38	106
B7	9	8	37	39	13	105
B8	2	7	18	33	46	106
B9	2	8	18	29	49	106
B10	3	7	15	27	54	106
B11	2	6	18	25	55	106
B12	2	9	23	40	32	106
B13	15	26	27	26	12	106
B14	1	2	23	34	46	106
B15	6	6	30	34	30	106
B16	12	17	29	25	23	106
B17	3	8	29	37	29	106
B18	4	6	25	40	31	106

Table 4.7 (cont’d)

B19	2	5	21	40	38	106

4.3.1 Relative Importance Index (RII):

This study utilizes the Relative Importance Index (RII) method, a widely recognized ranking technique, to evaluate the significance of various factors influencing the adoption of 3D printing technology in the construction sector. The RII method, which calculates importance based on response scores, is applied to both the drivers and barriers associated with this integration, as shown in Eq. (1).

$$\text{RII}(\%)=\frac{\Sigma\,\text{S}}{\text{H*N}} \qquad (1)$$

where;

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

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

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

For instance, the RII for ‘D1: Reduction in material’ is computed as illustrated in Eq. (2).

$$\text{RII}_{\text{D1}}=\frac{(2*1)+(5*2)+(12*3)+(32*4)+(55*5)}{5*106}=0.850943396 \qquad (2)$$

The Relative Importance Index (RII) values for each factor were computed, and the factors were subsequently ranked based on these RII values derived from 106 completed surveys, as presented in Table 4.8. The factor "D9- Faster construction" achieved the highest rank according to the RII, followed by "D5- Lower rate of site accidents and fatalities" in second place, "D1- Reduction in material waste" in third, and "D6- Higher energy efficiency in buildings due to improved insulation" in fourth. Conversely, the factor "D20- Freedom in design due to less strict standards" received the lowest rank, just after "D27- 3D printing enables mass-customization regardless of economies of scale" and "D16- Lower supervision cost".

Table 4.8: RII scores and ranks of the 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 energy efficiency in the buildings due to improved insulation	0.8490566
5	D8	Fast fabrication of the prototype	0.8490566
6	D13	Lower labor cost	0.84716981
7	D18	Enables implementing complex geometries easier and faster	0.83962264
8	D17	Lower indirect cost due to faster construction	0.83396226
9	D26	Higher quality of construction	0.82830189
10	D12	Lower material cost	0.80566038
11	D22	Enables direct transfer of design from a virtual environment (e.g., BIM) to the 3D printer	0.80566038
12	D2	The ability to have more customization and personalization in manufacturing with the use of diverse materials	0.80377358
13	D4	The ability to use materials such as metal, foam, geopolymer, etc. helps improve the sustainability of buildings	0.79811321
14	D15	Lower material transportation cost	0.79433962
15	D14	Lower material storage cost	0.79245283
16	D21	Higher flexibility to modify the design	0.79245283
17	D10	Productivity unaffected by the changing weather conditions	0.79056604
18	D7	Reduction in noise pollution	0.78113208
19	D3	Lower emissions from transportation due to the reduced materials and equipment requirements	0.77735849
20	D11	Involvement of fewer parties (i.e., suppliers, contractor, subcontractors) makes coordination simpler	0.77358491
21	D19	Lower self-weight of the structure (due to smaller structural 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 resources	0.76603774
24	D25	More efficient restoration and/or repairing of the existing facilities	0.76415094
25	D16	Lower supervision cost	0.76226415
26	D27	3D printing enables mass-customization regardless of economies of scale	0.76037736
27	D20	Freedom in design due to less strict standards	0.75283019

And also, Table 4.9 presents the RII values in percentages along with the ranking of the 19 barrier factors, based on responses from all 106 participants in this study's questionnaire. As indicated in Table 4.2, the most and least significant barriers in the Turkish construction industry were identified as follows. The top-ranked barrier, according to the RII score, was "B11: Lack of government regulations, standardizations, and building codes on 3D Concrete Printing (3DCP)." This was followed by "B10: Current technology is not ready for printing large-scale buildings," which ranked second, and "B14: Lack of knowledge about the usage of 3D printers for large-scale buildings," which ranked third. Conversely, the least important barrier was "B13: Cybersecurity risks associated with 3D printing," followed by "B16: Leads to job losses and difficulties in securing employment" and "B7: Layered and rough surface of the printed structures."

Table 4.9: RII scores and ranks of the barriers

Rank	**Barrier**	**Description**	**RII (%)**
1	B11	Lack of government regulations, standardizations, and building codes on 3D Concrete Printing (3DCP)	0.83584906
2	B10	Current technology is not ready for printing large-scale buildings	0.83018868
3	B14	Lack of knowledge about the usage of 3D printers for large-scale buildings	0.83018868
4	B4	Significant startup costs associated with this technology	0.82075472
5	B9	Reinforcement of concrete can be challenging	0.81698113
6	B8	Lack of knowledge about mechanical properties of the printed structures	0.81509434
7	B19	Lack of knowledge about buildability and/or workability of 3D printing materials	0.80188679
8	B1	Lack of knowledge about the sustainability of 3D printing materials	0.80000000
9	B6	High costs associated with the concrete used in 3D printing	0.77924528
10	B12	Complexity and risks associated with adoption of 3D printing technology in construction industry	0.77169811
11	B18	Resistance towards adoption of technological innovation by the industry	0.76603774
12	B5	Transportation of large 3D printers can be challenging and costly	0.75660377
13	B17	Requires specialized workforce for designing 3D objects and setting up the equipment	0.75283019
14	B2	Limited availability of insulating materials	0.74528302
15	B15	Errors in design and/or mistakes in printer settings can easily lead to losses, waste, and rework	0.74339623
16	B3	Possibility of negative impact on human health due to potentially harmful new substances	0.70754717
17	B7	Layered and rough surface of the printed structures	0.67358491
18	B16	Leads to job losses and difficulties in securing employment	0.65660377

Table 4.9 (cont'd)

19	B13	Cybersecurity risks associated with 3D printing	0.58867925

4.3.2 Pairwise Comparison of Drivers and Barriers

The next step after determining the Relative Importance Index (RII) is to perform a Pairwise Comparison of Drivers and Barriers using the Analytical Hierarchy Process (AHP). This step involves creating pairwise comparison matrices for the identified drivers and barriers, organized into their respective categories (e.g., technological, financial, regulatory) and subcategories. The matrices compare the relative importance of each factor using a scale of 1 to 5 in our survey, where 1 indicates equal importance, and 5 signifies extreme importance of one factor over another. However, it is important to note that the traditional AHP scale typically ranges from 1 to 9, allowing for finer granularity in judgment. Expert judgments or stakeholder inputs are used to populate these matrices, ensuring reciprocal values for inverse comparisons [128].

In the context of the provided data, Tables 4.10–4.14 present the pairwise comparison matrices for specific subcategories of drivers, while Tables 4.15–4.22 focus on the pairwise comparison matrices for specific subcategories of barriers. These subcategories encompass critical factors such as environmental impact, economic feasibility, and others. By systematically analyzing these matrices, the relative importance of each factor within its respective category is determined. The calculated weights are subsequently utilized to derive the overall priorities of the categories and subcategories, which play a crucial role in supporting effective and informed decision-making processes [128].

4.3.2.1 Consistency Check with the Consistency Ratio (CR)

To ensure the logical coherence of the pairwise comparisons, the Consistency Ratio (CR) is calculated. This step verifies whether the judgments used in the pairwise comparison matrices are consistent. The CR is computed using the Eq. (3) as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

Here, the Consistency Index (CI) is calculated as per Eq. (4):

$$CI = \frac{\lambda max - \eta}{\eta - 1} \tag{4}$$

where;

- λmax is the principal eigenvalue of the matrix, derived from the pairwise comparison results.
- η is the number of factors being compared.

The RI (Random Consistency Index) is a predefined value based on the matrix size and is taken from Saaty's standard table. If the CR is less than 0.10, the judgments are considered consistent. If not, the matrix requires revision to improve consistency [129].

This consistency check is crucial for validating the reliability of the calculated priority weights. After confirming consistency, the weights of the categories and subcategories are synthesized to derive the overall ranking of drivers and barriers. This ensures a robust and logical decision-making framework aligned with stakeholder priorities [129].

4.3.2.2 Pairwise Comparison of Driver Factors

Tables 4.10 to 4.14 provide a detailed pairwise comparison of factors influencing the adoption of 3D printing within five key driver categories: Environment, Time, Cost, Design, and Technology. The Environment category (Table 4.10) highlights factors such as material waste reduction and sustainable material use, emphasizing environmental sustainability. The Time category (Table 4.11) focuses on speed and efficiency, with faster construction and prototype fabrication identified as critical drivers. In the Cost category (Table 4.12), factors like reduced labor and material costs dominate, reflecting the financial benefits of 3D printing. The Design category (Table 4.13) showcases flexibility and innovation, prioritizing capabilities such as creating complex geometric shapes and enhancing aesthetic quality. Lastly, the Technology category (Table 4.14) underscores advancements like improved automation, precision, and integration of digital tools. Pairwise comparison is conducted to systematically evaluate the relative importance of each factor within its category, enabling a structured decision-making process through the Analytic Hierarchy Process (AHP). This approach ensures that the weights assigned to each factor accurately reflect their significance, providing an objective basis for prioritizing drivers in the adoption of 3D printing technology.

Table 4.10: Factors in the Driver's Environment Category: Pairwise Comparison

Factors	D1	D2	D3	D4	D5	D6	D7
D1	1.000	1.059	1.095	1.066	0.989	1.002	1.089
D2	0.945	1.000	1.034	1.007	0.934	0.947	1.029
D3	0.914	0.967	1.000	0.974	0.904	0.916	0.995
D4	0.938	0.993	1.027	1.000	0.928	0.940	1.022
D5	1.011	1.070	1.107	1.078	1.000	1.013	1.101
D6	0.998	1.056	1.092	1.064	0.987	1.000	1.087
D7	0.918	0.972	1.005	0.979	0.908	0.920	1.000

Table 4.11: Factors in the Driver's Time Category: Pairwise Comparison

Factors	D8	D9	D10	D11
D8	1.000	0.968	1.074	1.098
D9	1.033	1.000	1.110	1.134
D10	0.931	0.901	1.000	1.022
D11	0.911	0.882	0.979	1.000

Table 4.12: Factors in the Driver's Cost Category: Pairwise Comparison

Factors	D12	D13	D14	D15	D16	D17
D12	1.000	0.951	1.017	1.014	1.057	0.966
D13	1.052	1.000	1.069	1.067	1.111	1.016
D14	0.984	0.935	1.000	0.998	1.040	0.950
D15	0.986	0.938	1.002	1.000	1.042	0.952
D16	0.946	0.900	0.962	0.960	1.000	0.914
D17	1.035	0.984	1.052	1.050	1.094	1.000

Table 4.13: Factors in the Driver’s Design Category: Pairwise Comparison

Factors	D18	D19	D20	D21	D22
D18	1.000	1.085	1.115	1.060	1.042
D19	0.921	1.000	1.028	0.976	0.960
D20	0.897	0.973	1.000	0.950	0.934
D21	0.944	1.024	1.053	1.000	0.984
D22	0.960	1.041	1.070	1.017	1.000

Table 4.14: Factors in the Driver’s Technology Category: Pairwise Comparison

Factors	D23	D24	D25	D26	D27
D23	1.000	0.998	1.002	0.925	1.007
D24	1.002	1.000	1.005	0.927	1.010
D25	0.998	0.995	1.000	0.923	1.005
D26	1.081	1.079	1.084	1.000	1.089
D27	0.993	0.990	0.995	0.918	1.000

The weights for the drivers’ factors were determined through the analysis of their respective pairwise comparison matrices. Each matrix represents the relative importance of subcategories within a specific driver category, such as Environment, Time, Cost, Design, and Technology. By normalizing the matrices and calculating the priority vectors, the relative weights of the subcategories were derived. These weights reflect the contribution of each subcategory to its parent category, enabling a comprehensive evaluation of their influence. For example, within the Environment category, subcategories such as D1 through D7 were analyzed, and their respective weights were calculated. Similarly, the weights for other categories, including Time (D8-D11), Cost (D12-D17), Design (D18-D22), and Technology (D23-D27), were derived. These calculated weights, as summarized in Table 4.15, provide a structured understanding of the factors driving decision-making, facilitating their prioritization in subsequent analyses.

Table 4.15: Driver Factors Weight

Drivers’ Weight					
D1: 0.1487	D2: 0.1405	D3: 0.1359	D4: 0.1395	D5: 0.1504	D6: 0.1484
D7: 0.1365	D8: 0.2581	D9: 0.2666	D10: 0.2402	D11: 0.2351	D12: 0.1666

Table 4.15 (cont'd)

D13: 0.1752
D14: 0.1639
D15: 0.1642
D16: 0.1576
D17: 0.1724
D18: 0.2118
D19: 0.1951
D20: 0.1899
D21: 0.1999
D22: 0.2032
D23: 0.1971
D24: 0.1976
D25: 0.1966
D26: 0.2131
D27: 0.1956

4.3.2.3 Pairwise Comparison of Barrier Factors

Tables 4.17 to 4.22 present a detailed pairwise comparison of factors influencing barriers to the adoption of 3D printing technology, organized across seven key categories: Environment, Cost, Quality, Government, Risk and Uncertainties, Technology, and People. The Environment category (Table 4.17) examines barriers like the lack of sustainable materials and environmental health concerns, emphasizing ecological challenges. The Cost category (Table 4.18) addresses financial limitations, including high initial investment costs and maintenance expenses, which are critical barriers to adoption. In the Quality category (Table 4.19), issues such as suboptimal material performance and concerns about structural integrity are highlighted. The Government category (Table 4.20) focuses on regulatory challenges and the lack of supportive policies that hinder adoption. The Risk and Uncertainties category (Table 4.21) identifies barriers such as uncertainties about long-term material performance and the lack of standardization. The Technology category (Table 4.22) explores challenges related to insufficient technological maturity and the need for advanced equipment. Finally, the People category (Table 4.23) highlights workforce-related barriers, including the need for specialized skills and resistance to adopting new technologies. Pairwise comparison is employed to systematically assess the relative importance of these barriers within their respective categories, enabling a structured evaluation through the Analytic Hierarchy Process (AHP). This method ensures that the weights assigned to each barrier accurately reflect their significance, providing an objective framework for identifying and addressing the most critical challenges in 3D printing adoption.

Table 4.16: Factors in the Barrier's Environment Category: Pairwise Comparison

Factors	B1	B2	B3
B1	1.0000	1.0734	1.1307

Table 4.16 (cont’d)

B2	0.9316	1.0000	1.0533
B3	0.8844	0.9494	1.0000

Table 4.17: Factors in the Barrier’s Cost Category: Pairwise Comparison

Factors	B4	B5	B6
B4	1.000	1.084	1.053
B5	0.921	1.000	0.971
B6	0.949	1.030	1.000

Table 4.18: Factors in the Barrier’s Quality Category: Pairwise Comparison

Factors	B7	B8	B9
B7	1.000	0.826	0.824
B8	1.210	1.000	0.998
B9	1.213	1.002	1.000

Table 4.19: Factors in the Barrier’s Government Category: Pairwise Comparison

Factors	B10	B11
B10	1.000	0.993
B11	1.007	1.000

Table 4.20: Factors in the Barrier’s Risk and Uncertainties Category: Pairwise Comparison

Factors	B12	B13
B12	1.000	1.311
B13	0.763	1.000

Table 4.21: Factors in the Barrier’s Technology Category: Pairwise Comparison

Factors	B14	B15	B16
B14	1.000	1.104	1.250
B15	0.906	1.000	1.132
B16	0.800	0.883	1.000

Table 4.22: Factors in the Barrier's People Category: Pairwise Comparison

Factors	B17	B18	B19
B17	1.000	0.983	0.939
B18	1.018	1.000	0.955
B19	1.065	1.047	1.000

The weights for the barriers' factors were derived through the analysis of their respective pairwise comparison matrices. Each matrix evaluates the relative importance of subcategories within a specific barrier category, including Environment, Cost, Quality, Government, Risk and Uncertainties, Technology, and People. By normalizing the matrices and calculating the priority vectors, the relative weights of the subcategories were determined. These weights indicate the contribution of each subcategory to its parent category, allowing for a detailed understanding of their significance. For instance, in the Cost category, subcategories B4 through B6 were analyzed, and their individual weights were computed. Similarly, the weights for other categories, such as Environment (B1-B3), Quality (B7-B9), Government (B10-B11), Risk and Uncertainties (B12-B13), Technology (B14-B16), and People (B17-B19), were calculated. These weights, summarized in Table 4.23, provide valuable insights into the relative influence of various barriers, supporting their prioritization in decision-making processes.

Table 4.23: Barriers Factors Weight

Barriers' Weight					
B1: 0.3551	B2: 0.3308	B3: 0.3141	B4: 0.3483	B5: 0.3210	B6: 0.3307
B7: 0.2921	B8: 0.3536	B9: 0.3543	B10: 0.4982	B11: 0.5018	B12:0.4982
B13:0.5018	B14: 0.3696	B15: 0.3348	B16: 0.2956	B17: 0.3244	B18: 0.3301
B19: 0.3455					

4.3.3 Pairwise Comparison for Categories

The pairwise comparison for categories was conducted to determine the relative importance of each category in both drivers and barriers. This process began with the calculation of the Relative Importance Index (RII) for each category, as shown in

Tables 4.24 and 4.27 for drivers and barriers, respectively. The RII values provided a basis for prioritizing the categories by their perceived significance.

Following the RII analysis, pairwise comparison matrices were constructed for the categories of drivers and barriers. These matrices, presented in Tables 4.25 and 4.28, allowed for a systematic evaluation of the relative importance of each category compared to others. Each pairwise comparison was made using the fundamental AHP scale, and the matrices were normalized to compute the priority vectors for the categories.

The resulting weights for each category, derived from the priority vectors, are summarized in Table 4.27 for drivers and Table 4.29 for barriers. These weights reflect the relative influence of each category in the context of the study. For instance, among the drivers, categories such as Cost, Time, Technology, Environment, and Design were evaluated, with their weights highlighting their impact on decision-making processes. Similarly, for barriers, categories like Cost, Risk and Uncertainties, Quality, Government, Technology, People, and Environment were analyzed.

By completing this process, the study established a clear hierarchical structure of categories for both drivers and barriers, providing a robust foundation for subsequent decision-making and analysis. This structured approach ensures that the relative significance of each category is comprehensively understood and incorporated into the overall assessment framework.

Table 4.24: RII-Ranked Categories of Drivers for 3D Printing Adoption in Construction

RII Rank	Categories	RII Value
1	Cost	0.913207547
2	Time	0.890566038
3	Technology	0.835849057
4	Environment	0.796226415
5	Design	0.794339623

Table 4.25: Pairwise Comparison Between Categories and Driver Categories

Categories	Cost	Time	Technology	Environment	Design
Cost	1.0000	1.0254	1.0926	1.1469	1.1496
Time	0.9752	1.0000	1.0655	1.1185	1.1211
Technology	0.9153	0.9386	1.0000	1.0498	1.0523
Environment	0.8719	0.8941	0.9526	1.0000	1.0024
Design	0.8698	0.8920	0.9503	0.9976	1.0000

Table 4.26: Driver Categories Weight

Weight		
Cost: 0.2159	Time: 0.2105	Technology: 0.1976
Environment: 0.1882	Design: 0.1878	

Table 4.27: RII-Ranked Categories of Barriers for 3D Printing Adoption in Construction

RII Rank	**Categories**	**RII Value**
1	Cost	0.873584906
2	Risk and Uncertainties	0.805660377
3	Quality	0.790566038
4	Government	0.786792453
5	Technology	0.783018868
6	People	0.783018868
7	Environment	0.669811321

Table 4.28: Pairwise Comparison Between Categories and Barrier Categories

Categories	Cost	Risk and Uncertainties	Quality	Government	Technology	People	Environment
Cost	1.0000	1.0843	1.1050	1.1103	1.1157	1.1157	1.3042
Risk and Uncertainties	0.9222	1.0000	1.0191	1.0240	1.0289	1.0289	1.2028
Quality	0.9050	0.9813	1.0000	1.0048	1.0096	1.0096	1.1803
Government	0.9006	0.9766	0.9952	1.0000	1.0048	1.0048	1.1746
Technology	0.8963	0.9719	0.9905	0.9952	1.0000	1.0000	1.1690
People	0.8963	0.9719	0.9905	0.9952	1.0000	1.0000	1.1690
Environment	0.7667	0.8314	0.8473	0.8513	0.8554	0.8554	1.0000

Table 4.29: Barrier Categories Weight

Weight			
Cost**:** 0.1591	Risk and Uncertainties**:** 0.1467	Quality**:** 0.1439	Government: 0.1432
Technology: 0.1426	People: 0.1426	Environment: 0.1220	

4.3.4 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a structured decision-making method that decomposes complex problems into a hierarchical framework, enabling a systematic evaluation of factors. In this research, AHP is employed to assess both the drivers and barriers associated with the adoption of 3D printing in construction. This method integrates both qualitative and quantitative analyses, providing a robust approach for prioritizing factors[130].

The AHP process begins by defining the main objective—evaluating the role of 3D printing in construction—and structuring it into a hierarchy. At the top of the hierarchy is the overarching goal, followed by layers representing categories (e.g., drivers and barriers) and their respective subcategories [131]. Pairwise comparisons are then conducted within each layer to determine the relative importance of factors, using a standardized scale ranging from 1 to 9 to assess the influence of one factor over another.

From these comparisons, priority vectors are calculated for each category and subcategory. To ensure logical soundness, a consistency check is performed, verifying that the judgments in the pairwise comparisons align consistently [132]. Once the consistency is confirmed, the derived weights are used to establish the relative priorities of the factors.

This methodical process culminates in the construction of a weighted matrix that reflects the importance of all considered factors. The resulting priorities provide valuable insights into the influence of various drivers and barriers, facilitating informed decision-making. AHP is widely regarded as an effective tool for evaluating complex problems, especially in construction, due to its ability to integrate multiple criteria and dependencies [132, 133].

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Demographic Characteristics of Respondents

The demographic characteristics of the respondents reveal a wide range of professional backgrounds, organizational contexts, and knowledge levels regarding 3D printing in construction. In terms of organizational affiliation, the majority of participants (70.97%) were employed in private sector organizations, with the remaining 29.03% working in public sector entities (Fig. 5.1). The respondents' job descriptions varied, with a notable proportion serving as Project Managers (15.24%), followed by Design Engineers (14.29%) and Academic professionals (23.81%) (Fig. 5.2). A smaller group represented roles such as Technical Managers, Owners, and Consultant Engineers, while 20% of respondents indicated their job descriptions fell under 'Others'. The majority of respondents (93.40%) were Civil Engineers, with minor representation from other engineering disciplines such as Electrical and Industrial Engineers, as well as architects and business developers (Fig. 5.3).

In terms of professional experience, 44% of the respondents had 6 to 15 years of experience, with 34% reporting 1-5 years of experience, and 23% possessing 6 to 25 years of professional exposure (Fig. 5.4). Educationally, a diverse range of qualifications was observed, with 41% holding a Master's degree (M.Sc.), 35% possessing a Bachelor's degree (B.Sc.), and 30% having earned a Ph.D. (Fig. 5.5). Regarding the type of organization respondents were affiliated with, 38% worked for contractors, 27% were employed by academic institutions, and 17% were consultants, while 9% were employers and 10% identified as designers (Fig. 5.6). Furthermore, the majority of respondents (60%) were employed by organizations established over 30 years ago, indicating a prevalence of experience with long-standing entities, while smaller percentages worked in relatively younger organizations (Fig. 5.7).

The level of knowledge regarding 3D printing in construction was another crucial aspect of the survey. A significant portion of respondents (62%) reported low knowledge of 3D printing, while 32% had moderate knowledge and 12% exhibited high proficiency in the technology (Fig. 5.8). This distribution reflects the varying levels of awareness and expertise in the field, which is important for understanding the adoption and implementation barriers associated with 3D printing in construction. Additionally, in terms of company size, 60.95% of respondents were employed in large organizations with over 500 employees, while 18.10% worked in smaller companies with fewer than 100 employees. This demographic spread provides critical insights into the industry's engagement with 3D printing, illustrating how organizational scale might influence the adoption of innovative technologies and the perception of associated drivers and barriers.

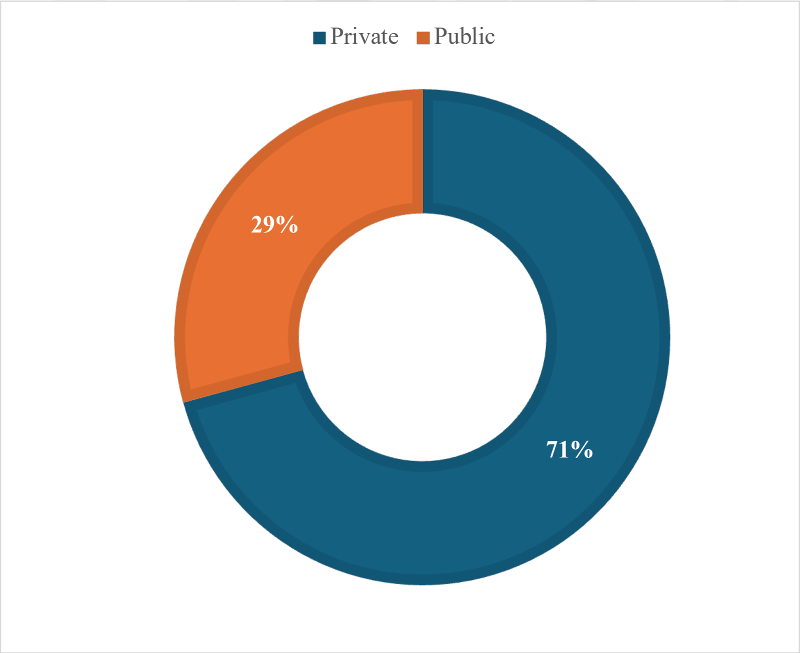

Figure 5.1: Respondents according to type of organization.

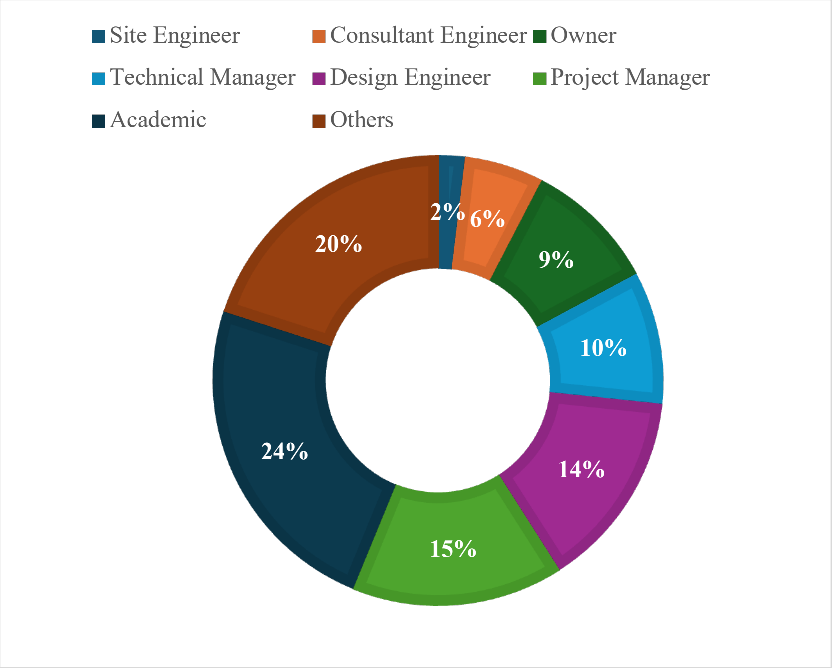

Figure 5.2: Respondents according to job description their organization.

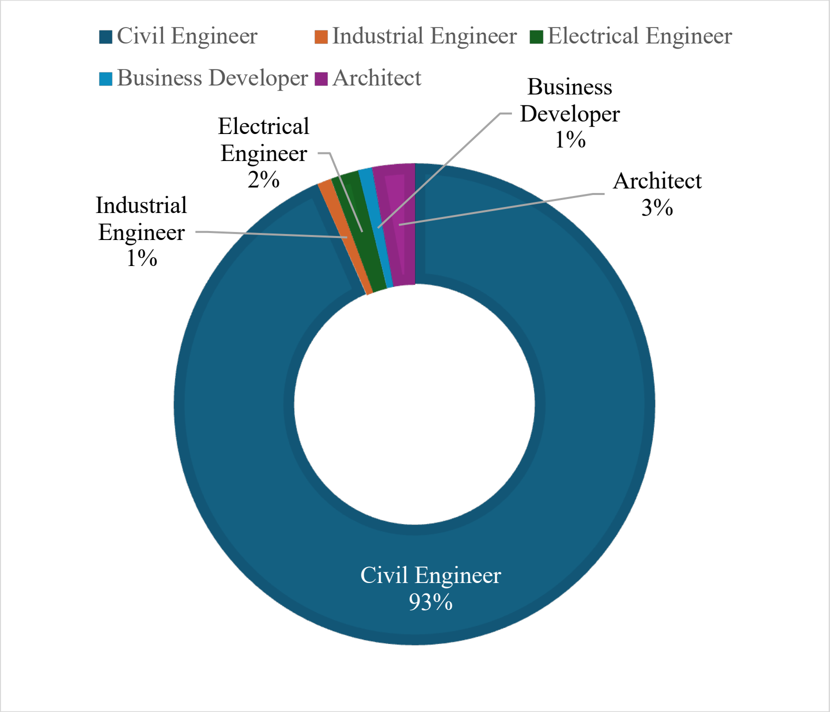

Figure 5.3: Respondents according to their profession.

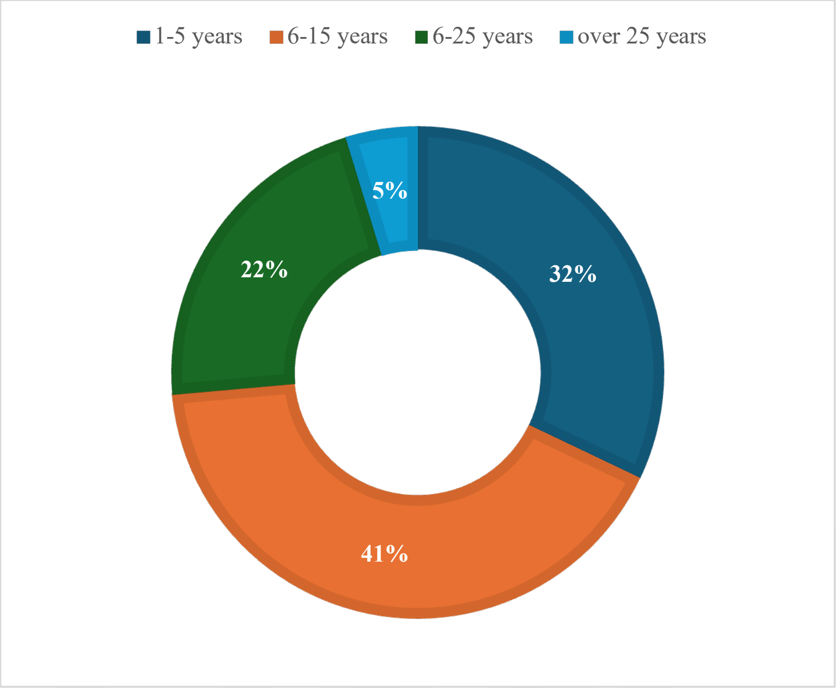

Figure 5.4: Respondents according to their Professional experience.

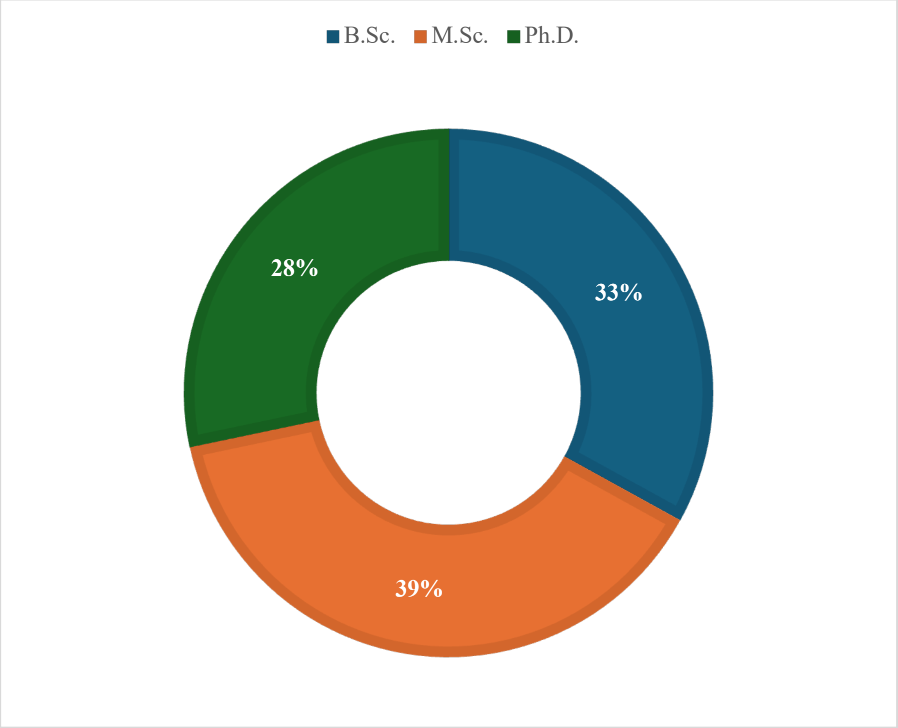

Figure 5.5: Respondents according to their Level of education.

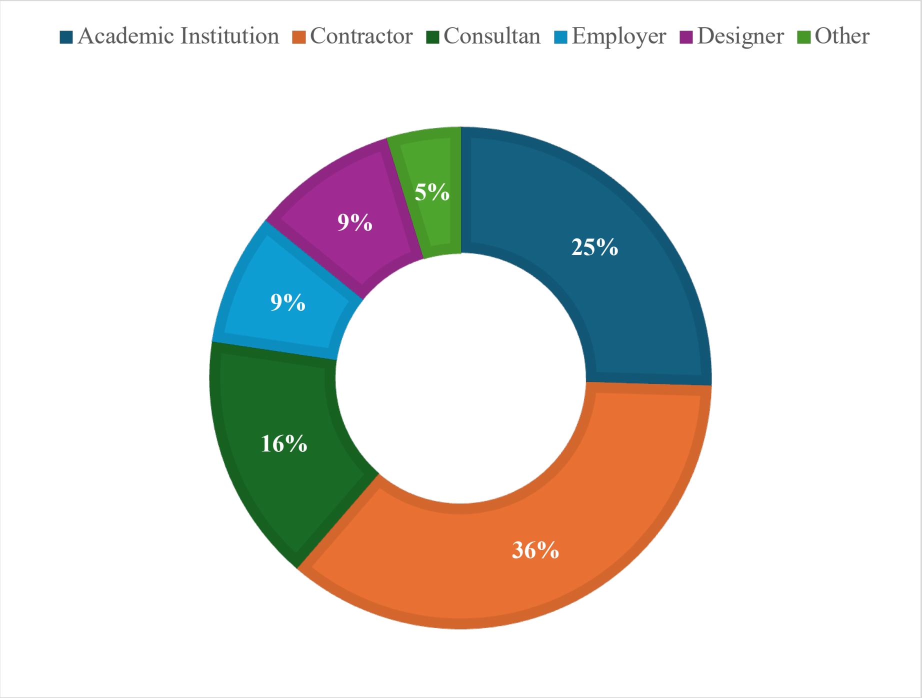

Figure 5.6: Respondents according to the type of organization they are working at.

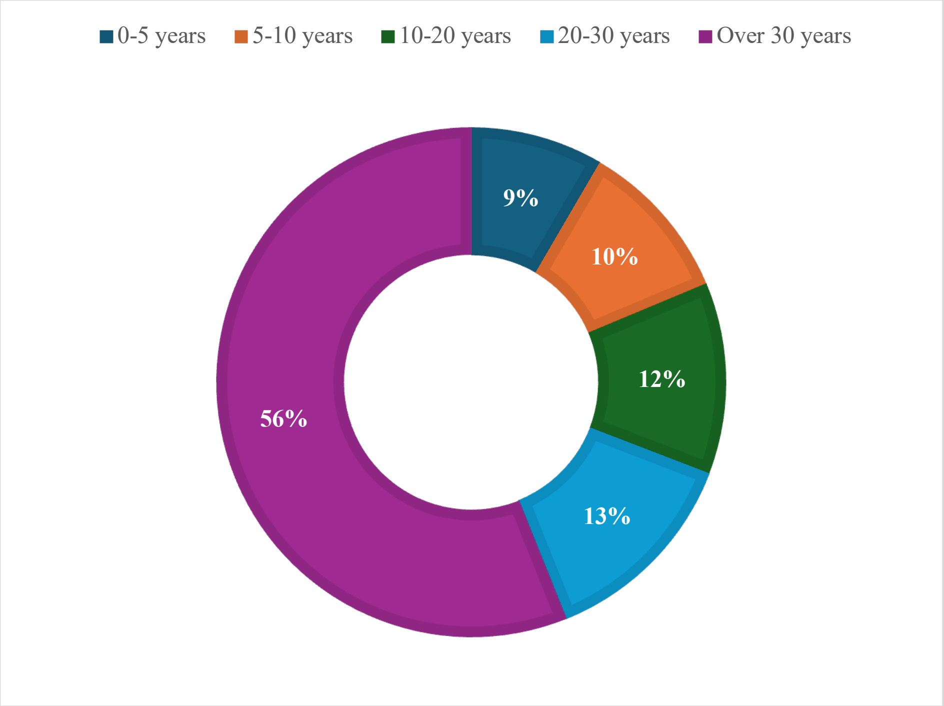

Figure 5.7: Respondents according to the age of the organization they are working at.

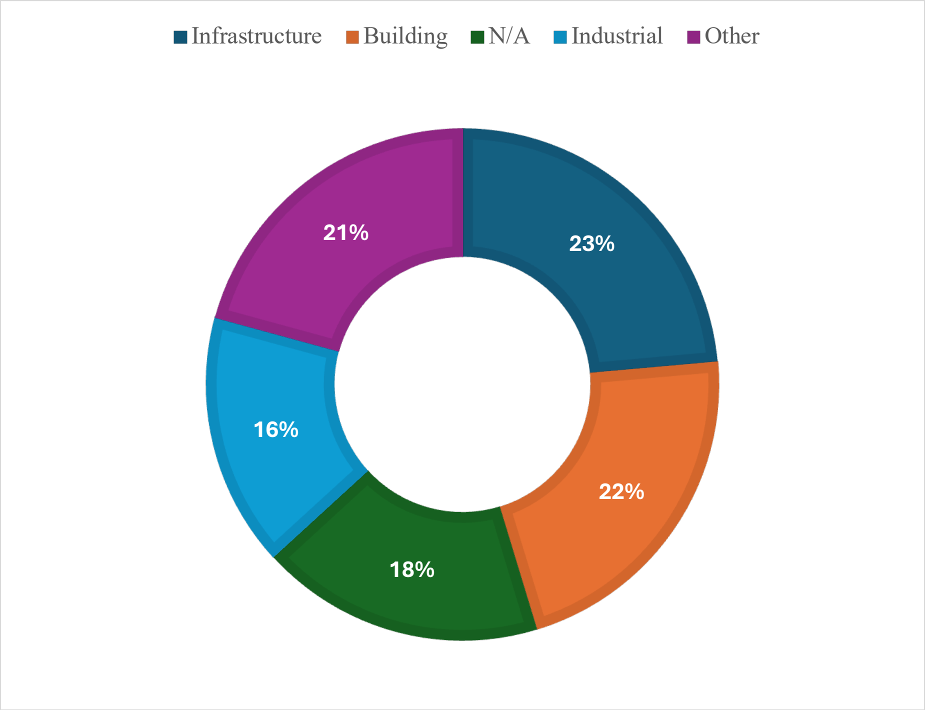

Figure 5.8: Respondents according to major field of activity of the organization.

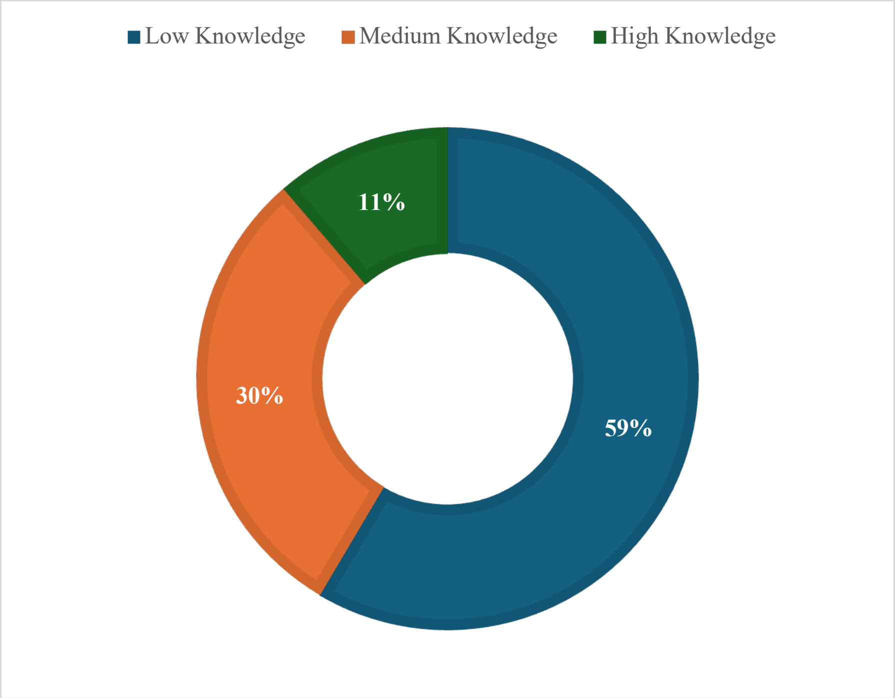

Figure 5.9: Respondents according to their knowledge of 3D Printing.

5.2 Comparative Analysis of Pairwise Evaluations for Barrier and Driver Categories

In the comparison of the "Cost" category between drivers and barriers, distinct RII values were observed. The RII for "Cost" as a driver was calculated to be 0.913207547, highlighting its critical importance as a factor promoting 3D printing adoption in the construction industry as shown in Table 4.14. Conversely, the RII for "Cost" as a barrier was slightly lower, at 0.873584906, indicating that while cost is a significant challenge, it is perceived as a slightly less critical barrier compared to its role as a driver as shown in Table 4.16. This comparison suggests that stakeholders recognize the cost benefits of 3D printing technologies, though cost-related concerns remain a notable hindrance to widespread adoption.

From other common points, "Technology" as a driver had an RII value of 0.835849057, whereas as a barrier, it scored lower at 0.783018868 This implies that while technological advancements are viewed as a strong driver for 3D printing adoption, there are still technological limitations that act as barriers, though to a lesser extent.
Similarly, for the "Environment" category, the RII value as a driver was 0.796226415, emphasizing its importance in encouraging 3D printing adoption. However, as a barrier, "Environment" had a significantly lower RII of 0.669811321, suggesting that environmental concerns, while relevant, are not viewed as major obstacles compared to their role as motivating factors.

5.3 AHP Analysis

The Analytical Hierarchy Process (AHP) was employed to prioritize both the drivers and barriers associated with the adoption of 3D printing in construction. Figures 5.10 and 5.11 present the AHP models developed for the drivers and barriers in this study. After constructing the models, the next step involves conducting pairwise comparisons within each category to determine local priorities. Following this, pairwise comparisons across categories are made to calculate the eigenvector. By multiplying the local priority vectors by this eigenvector, the limit matrix is obtained, which is then converted into AHP values, as shown in Table 5.1.

To derive the AHP values, the problem is structured hierarchically with a primary goal, criteria, and alternatives. Pairwise comparisons assess the relative significance of each factor, generating a comparison matrix. This matrix is then normalized to produce a priority vector, ensuring consistency via the Consistency Ratio (CR) and Consistency Index (CI). The resulting priority vectors are combined into a supermatrix, which undergoes normalization and is iteratively raised to a power until it converges. The final result is the limit matrix containing the AHP values. Through this systematic process, the weights of various categories and subcategories were determined, ultimately leading to the development of the final AHP tables for drivers (Table 5.1) and barriers (Table 5.2).

The systematic process outlined above culminates in the development of the final AHP models for drivers and barriers, as depicted in Figures 5.10 and 5.11. These models visually represent the hierarchical structure and the calculated weights of various categories and subcategories, offering a clear and concise framework for analyzing the factors influencing 3D printing adoption in construction. By integrating the priority values derived from the AHP methodology, these models serve as practical tools for identifying key drivers to leverage and barriers to address, ultimately guiding strategic decision-making in this emerging field.

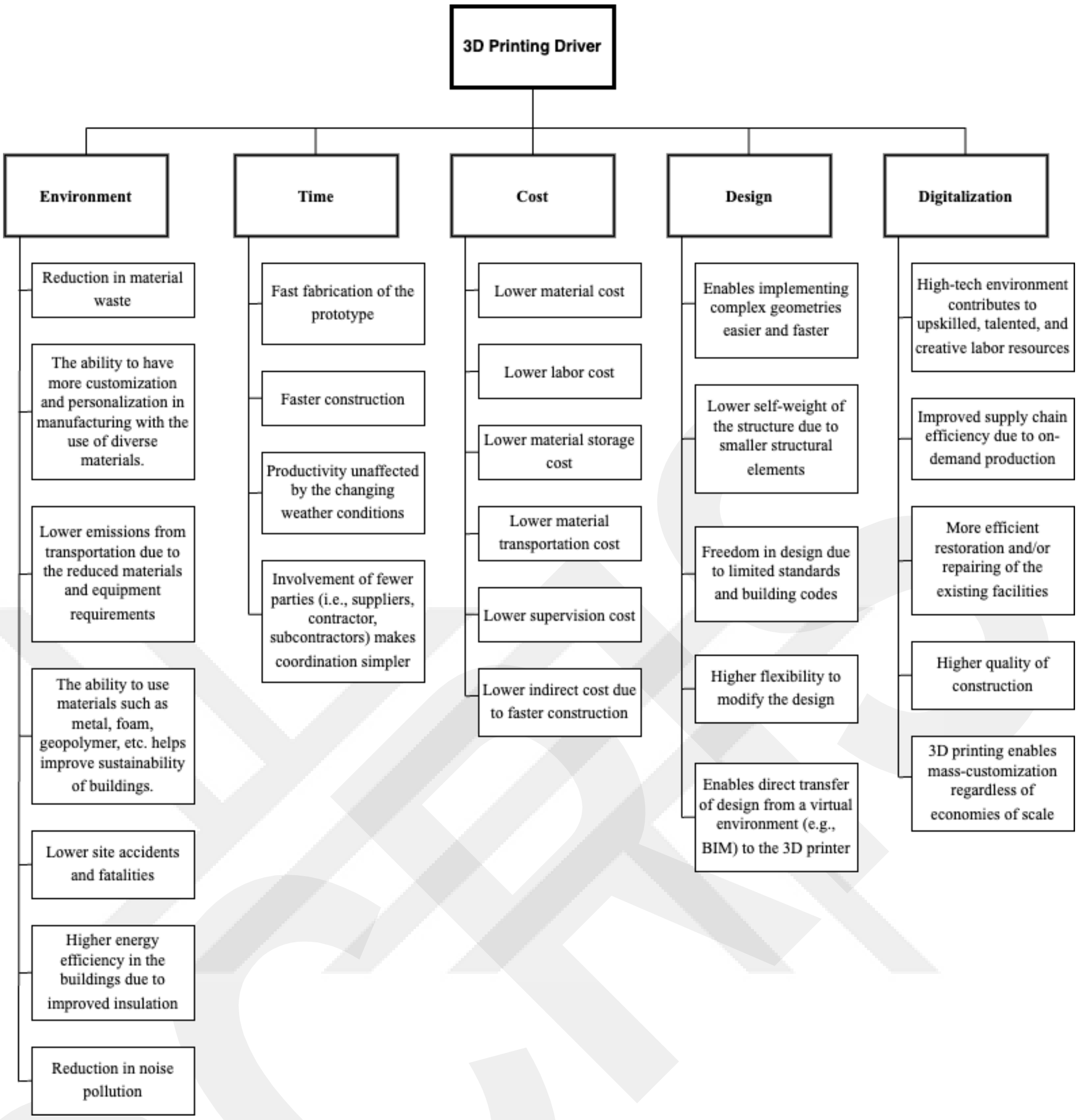

Figure 5.10: AHP model for Drivers.

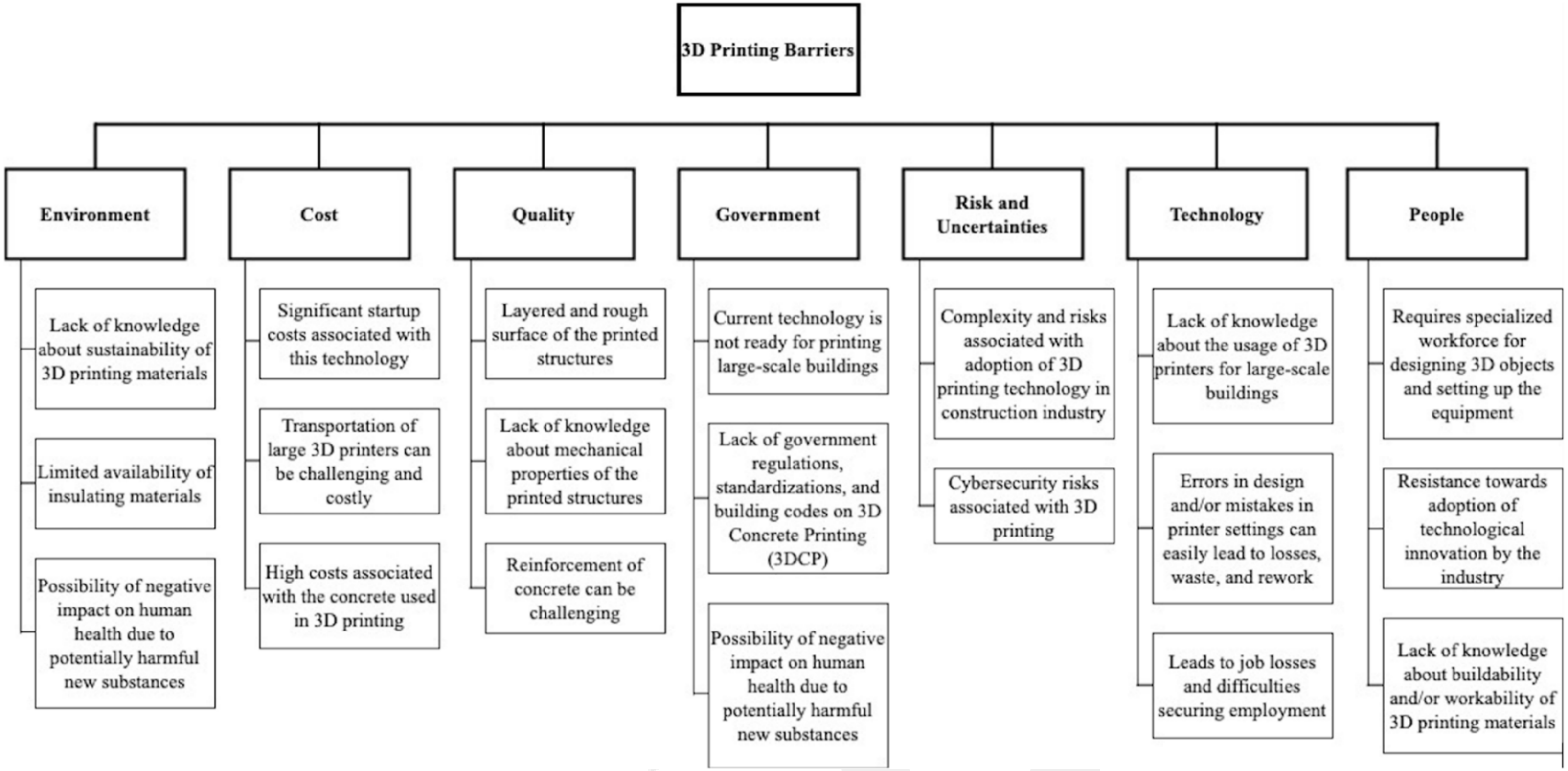

Figure 5.11: AHP model for Barriers.

5.3.1 AHP Results for Drivers

The process of constructing the AHP table for drivers began with categorizing the factors into five main categories: Environment, Time, Cost, Design, and Technology. Each category was further subdivided into specific subcategories to capture a detailed view of the drivers influencing the adoption of 3D printing.

5.3.1.1 Pairwise Comparison of Subcategories

Within each driver category, pairwise comparison matrices were created to evaluate the relative importance of the subcategories. For instance, in the Environment category, factors such as environmental sustainability, energy efficiency, and waste reduction were compared using the AHP scale of 1 to 9. The input from experts facilitated the calculation of normalized priority vectors, representing the weights of the subcategories within each category.

5.3.1.2 Pairwise Comparison of Categories

The significance of each driver category was evaluated through a pairwise comparison matrix (refer to Table 4.27). The resulting weights reflect the relative importance of each category in the context of 3D printing adoption in construction.

5.3.1.3 Final AHP Table for Drivers

The final weights for all driver subcategories were calculated by multiplying the weight of each subcategory by the weight of its parent category. These calculations were synthesized to create the Final AHP Table for Drivers, presented in Table 5.1, which provides a clear prioritization of the factors based on their influence.

Table 5.1: AHP Rankings and Weight Analysis of Key Drivers for 3D Printing Adoption in Construction

Category	**Drivers**	**AHP value**	**AHP rank**
Time	D9	0.056119	1
Time	D8	0.05433	2
Time	D10	0.050562	3

Table 5.1 (cont'd)

Time	D11	0.050562	4
Technology	D26	0.042109	5
Design	D18	0.039776	6
Technology	D24	0.039046	7
Technology	D23	0.038947	8
Technology	D25	0.038848	9
Technology	D27	0.038651	10
Design	D22	0.038161	11
Cost	D13	0.037826	12
Design	D21	0.037541	13
Cost	D17	0.037221	14
Design	D19	0.03664	15
Cost	D12	0.035969	16
Design	D20	0.035663	17
Cost	D15	0.035451	18
Cost	D14	0.035386	19
Cost	D16	0.034026	20
Environment	D5	0.028305	21
Environment	D1	0.027985	22
Environment	D6	0.027929	23
Environment	D2	0.026442	24
Environment	D4	0.026254	25
Environment	D7	0.025689	26
Environment	D3	0.025576	27

5.3.1.4 Key Insights

Table 5.1 provides a comprehensive ranking of the drivers influencing the adoption of 3D printing in construction, as determined by their AHP scores. The results highlight several key insights into the relative importance of different factors, grouping the drivers into distinct clusters based on their calculated weights. The scores for groups 1–4, 5, 6–20, and 21–27 are closely aligned, indicating minimal variation within these subsets. This clustering suggests that while some drivers hold higher significance, the differences within each group are relatively minor.

The top three factors based on AHP weights were:

- D9: Faster construction.
- D8: Fast fabrication of the prototype.

- D10: Productivity unaffected by the changing weather conditions.

These three factors fall under the Time category, emphasizing the importance of efficiency and time-saving benefits in the adoption of 3D printing technology. The high-ranking drivers reflect the industry's strong focus on faster project delivery and reduced delays caused by external factors like weather conditions.

Conversely, the three least significant drivers were:
- D4: The ability to use materials such as metal, foam, geopolymer, etc., helps improve the sustainability of buildings.
- D7: Reduction in noise pollution.
- D3: Lower emissions from transportation due to the reduced materials and equipment requirements.

These factors belong to the Environment category, reflecting their lower perceived importance compared to other drivers. While these environmental drivers offer potential long-term advantages, they are currently perceived as secondary considerations. The rankings derived purely from quantitative AHP calculations provide an objective basis for prioritization, underscoring a preference for tangible, immediate benefits over longer-term or indirect advantages.

5.3.2 AHP Results for Barriers

Similarly, the AHP table for barriers was developed to identify and prioritize the challenges associated with adopting 3D printing in construction. The barriers were grouped into seven main categories: Environment, Cost, Quality, Government, Risk and Uncertainties, Technology, and People.

5.3.2.1 Pairwise Comparison of Subcategories

Within each barrier category, pairwise comparison matrices were used to assess the relative importance of the subcategories. For example, in the Cost category, factors such as initial investment, operational costs, and maintenance costs were compared.

The normalized priority vectors derived from these comparisons represent the weights of the subcategories within each category.

5.3.2.2 Pairwise Comparison of Categories

A pairwise comparison of the barrier categories was conducted (refer to Table 4.29) to evaluate their overall significance. This step provided the weights for each barrier category, reflecting their relative impact on the adoption of 3D printing technology.

5.3.2.3 Final AHP Table for Barriers

The final weights of all barrier subcategories were determined by multiplying the weight of each subcategory by the weight of its parent category. The synthesis of these weights resulted in the Final AHP Table for Barriers, presented in Table 5.2, offering insights into the most critical barriers.

Table 5.2: AHP Rankings and Weight Analysis of Key Barriers for 3D Printing Adoption in Construction

Category	Barriers	AHP value	AHP rank
Risk and Uncertainties	B13	0.0736	1
Risk and Uncertainties	B12	0.0731	2
Government	B11	0.0719	3
Government	B10	0.0713	4
Cost	B4	0.0554	5
Cost	B6	0.0527	6
Technology	B14	0.0526	7
Cost	B5	0.0511	8
Quality	B8	0.0509	9
Quality	B9	0.0509	10
People	B19	0.0493	11
Technology	B15	0.0478	12
People	B18	0.047	13
People	B17	0.0462	14
Environment	B1	0.0433	15
Technology	B16	0.0421	16
Quality	B7	0.042	17
Environment	B2	0.0404	18
Environment	B3	0.0383	19

5.3.2.4 Key Insights

Table 5.2 provides a detailed ranking of the barriers to adopting 3D printing in construction, based on their Analytical Hierarchy Process (AHP) scores. The results reveal distinct groupings of barriers into subsets with closely aligned scores, including groups 1–4, 5–10, 11–18, and 19. The consistency of scores within these groups indicates minimal variation, highlighting the relative similarity in the perceived importance of barriers within each subset.

The top three factors based on AHP weights were:

- B13: Cybersecurity risks associated with 3D printing.
- B12: Complexity and risks associated with the adoption of 3D printing technology in the construction industry.
- B11: Lack of government regulations, standardizations, and building codes on 3D Concrete Printing (3DCP).

The first two factors belong to the Risk and Uncertainties category, underscoring significant concerns related to unpredictability in projects and industry apprehensions. The third-highest factor, categorized under Government, emphasizes the need for supportive regulatory frameworks to facilitate the adoption of innovative technologies.

Conversely, the three least significant factors were:

- B7: Requires specialized workforce for designing 3D objects and setting up the equipment.
- B2: Limited availability of insulating materials.
- B3: Possibility of negative impact on human health due to potentially harmful new substances.

The first of these factors belongs to the Quality category, while the last two belong to the Environment category. These findings suggest that while issues related to workforce specialization, material availability, and health concerns are important, they are perceived as less critical barriers compared to risk management and governance.

5.3.3 Comparison of AHP Results: Barriers vs. Drivers in 3D Construction Printing

The comparison of AHP results for drivers and barriers provides valuable insights into the priorities and challenges associated with adopting 3D printing in Türkiye's construction sector. The top-ranked drivers highlight the industry's focus on efficiency and time-saving benefits, with the highest-rated factors falling under the Time category. Specifically, D9 (Faster construction), D8 (Fast fabrication of the prototype), and D10 (Productivity unaffected by changing weather conditions) underscore the critical importance of streamlining project timelines and minimizing delays.

Conversely, the top-ranked barriers reflect concerns around uncertainty and governance. The highest-rated barriers, B13 (Cybersecurity risks), B12 (Complexity and risks of adoption), and B11 (Lack of government regulations), reveal the pressing need to address risks and establish robust regulatory frameworks to support the integration of 3D printing technology. The first two barriers belong to the Risk and Uncertainties category, while the third pertains to Government policies, signaling foundational issues that must be resolved to facilitate adoption.

Interestingly, environmental factors occupy the lowest ranks in both drivers and barriers. For drivers, environmental benefits such as D4 (Sustainability improvements), D7 (Noise reduction), and D3 (Lower emissions) are perceived as less critical compared to time-related efficiencies. Similarly, among barriers, B7 (Quality of printed structures) and environmental concerns like B2 (Limited insulating materials) rank the lowest, indicating that stakeholders currently prioritize immediate operational challenges over long-term environmental impacts.

These findings suggest that for 3D construction printing to gain traction in Türkiye, efforts should prioritize mitigating risks and uncertainties while strengthening regulatory support. Simultaneously, leveraging the time-saving advantages of the technology can drive adoption. While environmental considerations are secondary at present, integrating sustainability into future strategies may enhance the long-term viability and acceptance of 3D construction printing.

5.4 Recommendations and Future Directions

The findings of this study underline the importance of addressing both the drivers and barriers to facilitate the adoption of 3D printing in construction. To this end, the following measures are recommended:

- **Regulatory Frameworks:** Governments should develop and enforce clear regulations and standards for 3D printing in construction, particularly concerning material testing, safety, and environmental compliance [30], [134].
- **Knowledge Dissemination:** Educational initiatives and workshops should be launched to enhance awareness of 3D printing's capabilities, sustainability potential, and operational efficiency [75].
- **Technical Innovation:** Investments in advanced materials and post-processing techniques are necessary to address quality concerns and expand the applicability of 3D printing in high-precision projects [20].
- **Workforce Development:** Reskilling programs and training for construction professionals are crucial to overcoming resistance to technological adoption and ensuring a smooth transition to automation [126].

While 3D printing offers transformative potential for the construction industry, its adoption is contingent on overcoming significant barriers. By focusing on regulatory development, knowledge enhancement, and technical innovation, the industry can unlock the full benefits of 3D printing, fostering a sustainable and efficient future.

CHAPTER 6

CONCLUSION

In conclusion, this study successfully identified and analyzed the key drivers and barriers influencing the adoption of 3D printing technology in the construction industry, focusing on the Turkish construction sector. Through a comprehensive survey and the application of the Relative Importance Index (RII) and Analytic Hierarchy Process (AHP) models, the research offered valuable insights into the industry's perspective on 3D printing. The findings highlighted the reduction in material waste as the most critical driver, showcasing 3D printing's potential to enhance environmental sustainability in construction. The technology's ability to enable customization and the use of diverse materials further emerged as significant motivators. In contrast, the perceived impact of reduced supervision costs was ranked as the least influential driver.

Despite these advantages, several barriers continue to impede the widespread adoption of 3D printing. Chief among these challenges is the absence of clear governmental regulations, standardized building codes, and certification processes for 3D Concrete Printing (3DCP). This regulatory void creates uncertainty regarding safety, legal compliance, and material standards, discouraging industry professionals from adopting the technology. Similarly, technological limitations pose another significant hurdle. Current 3D printing systems lack the capacity to efficiently produce large-scale structures, making them unsuitable for many infrastructure projects. Issues such as achieving adequate concrete reinforcement and ensuring structural integrity further complicate its application.

Knowledge and expertise gaps also remain a major impediment, with many professionals lacking the necessary training to effectively implement 3D printing in large-scale projects. Moreover, uncertainties persist regarding the long-term mechanical properties and durability of 3D printed structures, particularly under varying environmental conditions. Addressing these concerns will be essential for building stakeholder confidence and ensuring the practicality of the technology in real-world applications.

Another critical concern is cybersecurity. The digital nature of 3D printing, which relies heavily on design files and data exchange, presents vulnerabilities to cyberattacks. Unauthorized access or manipulation of design files could result in compromised project integrity, financial losses, or safety risks. Robust cybersecurity measures are thus indispensable to safeguarding digital assets and fostering trust in the technology.

Overall, while 3D printing presents transformative opportunities for the construction sector, its integration requires overcoming significant regulatory, technical, and knowledge-related challenges. Addressing these barriers through clear regulatory frameworks, technological advancements, workforce training, and enhanced cybersecurity will be pivotal in unlocking the full potential of 3D printing, paving the way for a more innovative, efficient, and sustainable construction industry.

6.1 Limitations of the Study

1. **Technological Constraints**: The study is limited by the available 3D printing technologies at the time of research. Some advanced or emerging techniques may not have been included, potentially limiting the scope of the findings.
2. **Subjectivity in AHP Method**: The AHP method involves subjective judgments in the pairwise comparison process, which may introduce bias into the final decision-making outcomes. While efforts were made to minimize bias, this is an inherent limitation of the method.
3. **Sample Diversity in the Survey**: The survey was conducted exclusively within Turkey. While the findings provide valuable insights into the local context, they may not fully capture global trends or variations in perspectives across different countries or regions.

6.2 Directions for Future Studies

Future research can build on the findings of this study by exploring the following methods to gain deeper insights and broaden the scope of understanding in the field of 3D construction printing:

1. **Factor Analysis:** Factor analysis can be utilized to identify underlying variables or dimensions that influence the adoption of 3D construction printing. By reducing complex data into a smaller set of factors, this method can provide a clearer understanding of key drivers and barriers within the industry.
2. **Structural Equation Modeling (SEM):** SEM offers a robust approach to examine the relationships between multiple variables simultaneously. This method could help future researchers test and validate hypotheses about the interdependencies between technological, economic, and social factors influencing 3D construction printing. It would also allow for a more precise evaluation of causal relationships.
3. **Cross-Country Comparative Studies:** Expanding the research to other countries and regions would enable a comparative analysis of how different cultural, economic, and regulatory contexts shape the adoption of 3D construction printing. Using advanced methods like factor analysis and SEM in such international studies could highlight both commonalities and unique regional trends, offering a global perspective on the field.

By integrating these methods into future research, scholars can contribute to a more comprehensive and globally relevant understanding of the dynamics driving 3D construction printing.

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APPENDIX A

QUESTIONNAIRE

Exploring The Drivers and Barriers of 3d Printing Technology in The Construction Industry

The information gathered from the questionnaire below will contribute to a graduate project study carried out under the guidance of Dr. Saman Aminbakhsh (Assistant Professor and Thesis Supervisor) and Dr. Emre Caner Akçay (Associate Professor and Thesis Co-Supervisor).

Since the questionnaire responses will be evaluated in aggregate, no personal information, such as names, will be collected. Your insights will be kept strictly confidential and will serve solely as data for this academic study.

The purpose of this study is to evaluate the factors that facilitate or hinder the adoption of 3D printing technology within the construction industry. The study aims to explore solutions to meet the growing demand for rapid and cost-effective construction methods. By analyzing responses, we hope to identify key drivers and barriers to implementing this innovative technology.

The questionnaire consists of two sections: the first section gathers general information about respondents, while the second section addresses technical aspects, focusing on the probability of occurrence and impact of various drivers and barriers divided into distinct categories.

We thank you in advance for dedicating your valuable time to this academic study and for sharing your experiences with us to further our understanding of this important topic.

Best Regards,

VOLUNTEER PARTICIPATION FORM

CONSENT: Please select your choice below. If you are taking the survey physically in the field, you will be given a hard copy of this form. In case you are entering this survey online, you may print a copy of this consent form for your records. Clicking on the “AGREE” button indicates that,

- You have read the above information.

- You voluntarily agree to participate.

- You are 18 years of age or older.

☐ Agree ☐ Disagree

PART A: General information about the organization and the respondent

This section of the questionnaire comprises general questions related to the respondent’s occupation, qualifications, industry, and experience they have for working in that particular industry.

1- What type of organization do you work for?

☐ Public ☐ Private

2- What is your job description in your organization?

☐ Owner ☐ Site Engineer ☐ Project Manager ☐ Consultant Engineer ☐ Design Engineer ☐ Safety Engineer ☐ Technical Manager ☐ Technician ☐ Academic

☐ Other ………….……

3- What is your profession?

☐ Civil Engineering/Architectural ☐ Mechanical Engineering ☐ Electrical Engineering

☐ Chemical Engineering ☐Petroleum Engineering ☐ Other ………….……

4- Professional Experience:

☐ 1-5 years ☐ 6-15 years ☐ 16-25 years ☐ Over 25 years

5- Level of Education:

☐ B.Sc. ☐ M.Sc. ☐ Ph.D.

6- The type of organization you are working at:

☐ Academic Institution ☐ Employer ☐ Contractor
☐ Consultant ☐ Designer Other ………….……

7- The age of the organization you are working at:

☐ 0-5 years ☐ 5-10 years ☐ 10-20 years ☐ 20-30 years ☐ Over 30 years

8- Field of activity of the organization:

☐ Building ☐ Infrastructure ☐ Industrial ☐ N/A

☐ Other ………….………

9- What is the size of your organization?

☐ Below 100 employees ☐ 100-250 employees

☐ 250-500 employees ☐ Over 500 employees

10- Have you had any prior working/research experience with 3D printing?

☐ Yes ☐ No

Part B. DRIVERS (Factors)

Please rate your agreement on the following drivers for the implementation of 3D printing technology in construction projects (1-Strongly Disagree, 2- Disagree, 3- Neutral, 4- Agree, 5- Strongly Agree).

No	Drivers	Score				
		1	2	3	4	5
D1	Reduction in material waste	1	2	3	4	5
D2	The ability to have more customization and personalization in manufacturing with the use of diverse materials	1	2	3	4	5
D3	Lower emissions from transportation due to the reduced materials and equipment requirements	1	2	3	4	5
D4	The ability to use materials such as metal, foam, geopolymer, etc. helps improve the sustainability of buildings	1	2	3	4	5
D5	Lower site accidents and fatalities	1	2	3	4	5
D6	Higher energy efficiency in the buildings due to improved insulation	1	2	3	4	5
D7	Reduction in noise pollution	1	2	3	4	5
D8	Fast fabrication of the prototype	1	2	3	4	5
D9	Faster construction	1	2	3	4	5
D10	Productivity unaffected by the changing weather conditions	1	2	3	4	5
D11	Involvement of fewer parties (i.e., suppliers, contractor, subcontractors) makes coordination simpler	1	2	3	4	5
D12	Lower material cost	1	2	3	4	5
D13	Lower labor cost	1	2	3	4	5
D14	Lower material storage cost	1	2	3	4	5
D15	Lower material transportation cost	1	2	3	4	5
D16	Lower supervision cost	1	2	3	4	5

D17	Lower indirect cost due to faster construction	1	2	3	4	5
D18	Enables implementing complex geometries easier and faster	1	2	3	4	5
D19	Lower self-weight of the structure due to smaller structural elements	1	2	3	4	5
D20	Freedom in design due to limited standards and building codes	1	2	3	4	5
D21	Higher flexibility to modify the design	1	2	3	4	5
D22	Enables direct transfer of design from a virtual environment (e.g., BIM) to the 3D printer	1	2	3	4	5
D23	High-tech environment contributes to upskilled, talented, and creative labor resources	1	2	3	4	5
D24	Improved supply chain efficiency due to on-demand production	1	2	3	4	5
D25	More efficient restoration and/or repairing of the existing facilities	1	2	3	4	5
D26	Higher quality of construction	1	2	3	4	5
D27	3D printing enables mass-customization regardless of economies of scale	1	2	3	4	5

(Optional)

Would you like to contribute any additional drivers to the questionnaire, based on your knowledge and experience, that you believe are significant in the context of 3D printing technology in construction?

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PART C: DRIVERS (CATEGORIES)

Five categories including **Environment**, **Time**, **Cost**, **Design**, and **Technology** can act as drivers in the adoption of 3D printing technology in the Turkish construction industry. Please rate the importance of these categories using the 5-Point Likert scale (**1-**Not at all important | **2-**Slightly important | **3-**Moderately important | **4-**Very important | **5-**Extremely important).

No	**Drivers (Categories)**	**Score**				
		1	**2**	**3**	**4**	**5**
1	Environment	1	2	3	4	5
2	Time	1	2	3	4	5
3	Cost	1	2	3	4	5
4	Design	1	2	3	4	5
5	Technology	1	2	3	4	5

Part D. BARRIERS (Factors)

Please score the significance of the following barriers in the implementation of 3D printing technology in construction projects using the 5-Point Likert scale (**1-**Not at all important | **2-**Slightly important | **3-**Moderately important | **4-**Very important | **5-**Extremely important).

No	**B: Barriers**	**Score**				
		1	**2**	**3**	**4**	**5**
B1	Lack of knowledge about sustainability of 3D printing materials	1	2	3	4	5
B2	Limited availability of insulating materials	1	2	3	4	5
B3	Possibility of negative impact on human health due to potentially harmful new substances	1	2	3	4	5
B4	Significant startup costs associated with this technology	1	2	3	4	5
B5	Transportation of large 3D printers can be challenging and costly	1	2	3	4	5
B6	High costs associated with the concrete used in 3D printing	1	2	3	4	5
B7	Layered and rough surface of the printed structures	1	2	3	4	5

B8	Lack of knowledge about mechanical properties of the printed structures	1	2	3	4	5
B9	Reinforcement of concrete can be challenging	1	2	3	4	5
B10	Current technology is not ready for printing large-scale buildings	1	2	3	4	5
B11	Lack of government regulations, standardizations, and building codes on 3D construction printing (3DCP)	1	2	3	4	5
B12	Complexity and risks associated with adoption of 3D printing technology in construction industry	1	2	3	4	5
B13	Cybersecurity risks associated with 3D printing	1	2	3	4	5
B14	Lack of knowledge about the usage of 3D printers for large-scale buildings	1	2	3	4	5
B15	Errors in design and/or mistakes in printer settings can easily lead to losses, waste, and rework	1	2	3	4	5
B16	Leads to job losses and difficulties securing employment	1	2	3	4	5
B17	Requires specialized workforce for designing 3D objects and setting up the equipment	1	2	3	4	5
B18	Resistance towards adoption of technological innovation by the industry	1	2	3	4	5
B19	Lack of knowledge about buildability and/or workability of 3D printing materials	1	2	3	4	5

(Optional)

Would you like to contribute any additional barriers or drivers to the questionnaire, based on your knowledge and experience, that you believe are significant in the context of 3D printing technology in construction?

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PART E: BARRIERS (CATEGORIES)

No	B: Barriers	Score

		1	**2**	**3**	**4**	**5**
1	Environment	1	2	3	4	5
2	Cost	1	2	3	4	5
3	Quality	1	2	3	4	5
4	Government	1	2	3	4	5
5	Risks and Uncertainties	1	2	3	4	5
6	Technology	1	2	3	4	5
7	People	1	2	3	4	5

(Optional)

As we develop our report, we may find it helpful to reach out for you (for follow-up questions or requesting for more clarifications). Would you be willing to be contacted in case it is required? If so, please provide your contact information (Email address and/or phone number).

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Your valuable time and effort are greatly appreciated.