

Review

On the Effects of Additive Manufacturing on Affordable Housing Development: A Review

Mahmoud Bayat ^{1,*}, Subham Kharel ² and Jianling Li ²

¹ School of Architecture, College of Architecture, Planning and Public Affairs, The University of Texas at Arlington, Arlington, TX 76000-76099, USA

² Department of Public Affairs and Planning, College of Architecture, Planning and Public Affairs, The University of Texas at Arlington, Arlington, TX 76000-76099, USA; sxk7802@mavs.uta.edu (S.K.); jjli@uta.edu (J.L.)

* Correspondence: mahmoud.bayat@uta.edu

Abstract: Additive manufacturing (AM) or 3D printing is transforming the construction industry by enabling the production of complex structures and components from digital blueprints using materials like concrete, plastics, and recycled materials. This technology reduces material waste, lowers production costs, and opens new possibilities for sustainable and affordable housing. Traditionally used for prototypes and low-volume production, AM has advanced into the architecture, engineering, and construction (AEC) sectors, offering potential solutions to the affordable housing crisis. Concrete 3D printing, for example, can reduce carbon emissions through the use of alternative materials, minimizing the need for raw resources. Additionally, the ability to optimize material usage and reduce construction waste through techniques like prefabrication and rapid construction can significantly lower the cost of building homes. This paper discusses how AM can contribute to addressing the challenges of affordable housing by exploring its applications in construction, its potential for reducing environmental impacts, and its role in improving cost-effectiveness. By integrating AM into manufactured housing models, it becomes possible to develop sustainable, cost-effective homes on a larger scale, which offers a promising solution to the growing demand for affordable housing. Through the widespread adoption of 3D printing technologies, it is feasible to address both affordability and sustainability concerns in the housing sector.



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1. Introduction

According to the U.S. Department of Housing and Urban Development (HUD), housing is considered affordable when the occupant spends no more than 30% of their gross income on housing costs, including their rent or mortgage, utilities, and insurance. However, affordability is also context-dependent, being influenced by local median incomes, housing market dynamics, and the availability of public subsidies [1]. This study analyzes the implications of additive manufacturing (AM) for affordable housing through two lenses. First, in the context of the mainstream construction and real estate industries, AM has the potential to reduce production costs, streamline construction workflows, and offer alternative building systems that can increase supply while mitigating labor shortages. This could shift market dynamics, especially in underbuilt segments such as low-rise multifamily housing. Second, from the perspective of alternative housing for the homeless

or precariously housed populations, including those residing in vehicles or informal shelters, AM offers scalable, modular construction methods that could support transitional or emergency shelters. Organizations such as ICON and Mobile Loaves & Fishes have piloted 3D-printed housing units for chronically homeless individuals, signaling the viability of AM as a humanitarian response tool [2]. Thus, the scope of AM's impact on housing affordability spans both formal market interventions and alternative shelter strategies for marginalized populations [3–6].

In the United States, manufactured housing—commonly known as mobile homes or trailers—serves as a primary source of affordable, unsubsidized housing, providing shelter to approximately 18 million people [7,8]. Manufactured homes are built in factories using a permanent chassis and then transported to their final location, which significantly reduces construction costs [7]. While they make homeownership more accessible for low-income households, these homes are often associated with stigma due to perceptions of poor quality and impermanence [9–11]. Despite improvements in quality control and adherence to the federal building standards published in 1976, challenges related to infrastructure, financing, and varied tenure arrangements continue to affect residents' affordability and security [11].

These homes are found both in metropolitan and nonmetropolitan areas, with a significant portion of them being in mobile home parks, where residents face additional risks, such as rising land rents and deteriorating infrastructure [12]. Despite these challenges, manufactured housing remains an essential source of affordable housing, particularly for low- and middle-income families. With growing housing demands, especially among vulnerable populations, there is an increasing need for innovative solutions. One promising approach is the integration of additive manufacturing (3D printing) in the construction of manufactured homes. This technology offers the potential to reduce construction costs, improve sustainability, and address some of the quality and infrastructure concerns associated with traditional manufactured housing methods.

Additive manufacturing, commonly known as 3D printing, is revolutionizing the construction and industrial sectors by enabling low-volume production runs and the production of complex geometries, prototypes, and small objects [13]. The process involves gradually adding material to create objects or structures from digital blueprints, which are designed using computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. The digital model is divided into thin layers, and material is deposited layer by layer, with each layer being bonded to the one below it until the product is complete [14]. Initially used for simpler applications, additive manufacturing has now expanded significantly into the architecture, engineering, and construction (AEC) industries. For example, Vinodh et al. (2009) [15] demonstrated the use of digital blueprints to 3D print an electronic switch knob, while Wu et al. (2016) [8] explored materials like nylon and plastic in producing small building components such as electrical [12] fittings, window frames, and plumbing fixtures. More recently, 3D printing has enabled the creation of strong, lightweight panels and facade systems with diverse design possibilities. Complex building components, including interior and exterior walls, columns, and beams, can now be produced using additive manufacturing methods like contour crafting (CC), which uses CAD and CAM to generate intricate surface designs [16].

One of the most promising applications of additive manufacturing lies in reducing the amount of embodied carbon in construction materials, which is essential for creating more sustainable and affordable housing. Concrete, a widely used building material, is a major contributor of carbon dioxide (CO₂) emissions due to the methods of producing of Portland cement. However, efforts are being made to lower the amount of embodied carbon in concrete by incorporating alternative materials like fly ash, slag, crushed recycled concrete, and other waste products into the mix [17]. These methods not only mitigate carbon

emissions but also help reduce landfill waste. Additive manufacturing contributes to this sustainability goal by enabling the use of recycled materials, reducing the need for new raw materials, and facilitating waste diversion. Moreover, the ability to reuse materials from demolished buildings plays a key role in conserving valuable resources and lowering the demand for newly manufactured materials [18]. In addition to its environmental benefits, 3D printing offers significant cost reductions. By optimizing material usage and reducing waste, 3D printing lowers production costs compared to traditional construction methods. This efficiency can make housing more affordable by reducing construction expenses, leading to lower housing prices. Consequently, additive manufacturing helps reduce the overall carbon footprint of construction projects while making housing more cost-effective, and thus supports both sustainability and affordability in the construction industry.

From an economic perspective, the additive manufacturing of affordable housing offers a variety of benefits. Rapid construction using 3D printing increases the production rate of housing while reducing labor costs, which could help lower housing prices. The cost of constructing new homes is a major factor influencing the value of existing housing, as higher construction costs make new builds less viable. Additive manufacturing techniques have the potential to break this cycle by reducing construction costs, making affordable housing more accessible. In addition, traditional construction methods generate considerable waste, with two tons of garbage being produced on average during the construction of a home [19]. Through the incorporation of prefabrication techniques, the use of additive manufacturing can reduce construction waste by up to 50% [20]. This technology allows for more efficient material use, eliminating waste from cutting materials to size and even allowing the printing of foundations and walls without traditional formwork. Furthermore, many 3D printing companies now prefabricate roofs with timber trusses, which also reduces waste. As a result, prefabricating 3D-printed homes in factories and then assembling them on-site has gained popularity, and ensures precise material use with minimal waste. This approach has been linked to cost savings in construction, with organizations like Habitat for Humanity reporting a 15% reduction in the average cost of a home due to waste reduction [21].

Given the ongoing challenges in addressing the growing demand for affordable housing, this literature review explores the potential of combining additive manufacturing (AM) with manufactured homes as a transformative solution. Additive manufacturing, particularly 3D printing, offers significant benefits, such as waste reduction, lower carbon emissions, and the ability to optimize construction methods for efficiency and flexibility. On the other hand, manufactured homes, while known for their cost-effectiveness and scalability, face several significant challenges that limit their broader adoption as a solution to the affordable housing crisis. Historically, these homes have been viewed as substandard or temporary housing, which has led to a lack of acceptance within communities. While significant advancements have been made in the design and quality of modern manufactured homes, the stigma persists, which can make it difficult for residents to access financing or for municipalities to approve them in certain areas [22,23]. By integrating these two technologies, it is possible to address the housing affordability crisis in a more sustainable and efficient manner. AM could enhance the construction of manufactured homes, reducing the associated production time, costs, and material waste while increasing the potential for customization and adaptability. This combination could unlock new possibilities for producing high-quality, low-cost housing at a scale that meets the needs of low- and middle-income families. The widespread adoption of both additive manufacturing and manufactured housing holds the potential to significantly increase housing accessibility, alleviate the affordability crisis, and provide a sustainable solution for the future of housing.

2. Literature Review

This section explores how additive manufacturing (AM) can play a role in addressing the challenges of affordable housing. First, it discusses the existing affordable housing challenges, then introduces manufactured housing as a solution, which is followed by an examination of AM and its applications, and, in conclusion, a synthesis of how these elements can be interconnected.

2.1. Affordable Housing and Related Challenges

The rapid growth of the world's urban population has brought forth one of the most urgent challenges of our time: the need to expand the supply of urban housing, particularly that of low-cost or affordable options, while also preserving and efficiently managing existing infrastructure [24]. Affordable housing has thus emerged as a crucial issue in the global discourse on sustainable urban development, particularly given the growing demand for housing across both developed and developing nations [25,26]. By its simplest definition, affordable housing refers to housing that can be rented or purchased by households earning at least the local average income, based on official public measures, regardless of the household's overall financial capacity. However, it is important to note that the specific definition of affordable housing varies significantly by region and can change over time depending on a host of factors, including local economic conditions, government policies, and housing market dynamics [27].

The importance of affordable housing extends far beyond the provision of basic shelter. Housing quality and accessibility have a profound impact on individuals' and communities' well-being. Studies have shown that affordable housing is strongly linked to a range of positive outcomes, including physical health [28], reduced psychological distress [29], improved educational performance [30], and even better dietary outcomes [31]. The significance of affordable housing as a determinant of public health and social equity is clear. In contrast, a shortage of affordable housing can have dire consequences, contributing to mental and physical health challenges and exacerbating socio-economic inequality [32,33].

The United States is facing a particularly severe crisis in affordable housing, which has become a nationwide issue, particularly for low-income renters (Figure 1) [34]. According to the Joint Center for Housing Studies of Harvard University, millions of American renters are now severely cost-burdened, spending more than 30% of their income on housing costs [35]. In fact, 23.9% of renters are facing an extreme financial burden, spending more than half of their income just to cover rent and utility bills. This growing financial strain is compounded by the ongoing under-building of affordable housing units. Particularly lacking are small multifamily housing options, which are critical to meeting the needs of low-income renters [36]. As a result, the shortfall of affordable units is increasing year by year, which is deepening the housing crisis and limiting economic mobility for many Americans. The shortage of affordable housing has sparked widespread public concern, with 49% of Americans acknowledging that the lack of affordable housing in their local communities is a major issue [37]. A significant majority of respondents in public opinion surveys have also expressed support for increasing the supply of affordable housing [38,39]. Despite this high level of awareness and support, however, numerous barriers continue to obstruct the construction of affordable housing units.

One of the most significant barriers to affordable housing development is local public opposition. This opposition often results in costly construction delays, additional design revisions, and even the outright denial of proposed projects [40]. The resistance to affordable housing is not just a social or political issue but has significant economic consequences, reducing the supply of available housing and driving up costs for low-income households. Moreover, zoning laws, which control the types of developments permitted in specific areas,

have been identified as another major factor that is driving up housing costs. Restrictive zoning regulations, particularly those that limit the construction of multifamily housing or reduce housing density, reduce the overall supply of rental housing and increase housing costs for renters [41,42]. In addition, zoning policies often contribute to racial segregation by disproportionately limiting affordable housing options in neighborhoods with higher proportions of low-income or minority residents, further entrenching inequality in urban areas [43].

Affordable Housing per hundred low-income renters by state

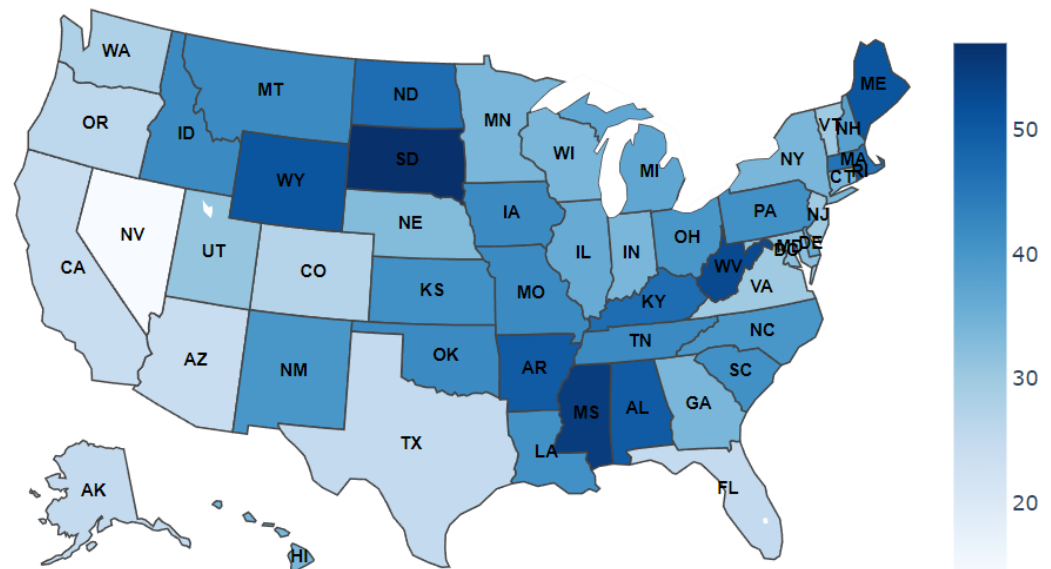


Figure 1. Affordable housing for low-income renters in 2024.

This ongoing shortage of affordable housing, compounded by socio-political resistance, underscores the critical need for innovative solutions that can address both the financial and social challenges of housing development. In response to this, many affordable housing scholars have explored innovative approaches to addressing housing shortages, with particular emphasis being placed on the use of sustainable and alternative building materials and techniques [44–46]. Over time, such approaches have led to the development and widespread use of temporary affordable housing solutions in the United States, particularly in response to housing crises or post-disaster recovery scenarios. Among the more established alternatives is manufactured housing, which has provided a vital source of affordable homes, especially for low-income households. Manufactured homes—often seen as a practical, cost-effective option—have become a critical part of the affordable housing landscape, addressing some of the most pressing housing challenges in urban and rural areas. In the following section, we will examine how manufactured housing contributes to affordability and its evolving role in the U.S. housing market.

2.2. Manufactured Housing as a Solution to Affordable Housing

In the United States, manufactured houses—mobile homes or trailers—are the primary source of reasonably priced, unsubsidized housing [47], housing about 18 million people. In contrast to conventional site-built homes, manufactured homes are produced in factories using a permanent chassis before being delivered to their final installation places [7]. The cost of these units is significantly reduced by their factory-based production, which makes them a necessary choice for low-income households (Figure 2). However, this building technique has also fueled the pervasive belief that manufactured homes are of lower quality

and are not permanent [9,10]. These housing units contribute significantly to the supply of inexpensive housing in American cities and rural areas [48–50]. About 46% of manufactured housing units, or 2.98 million units, are in metropolitan areas, with the remaining 54% being in nonmetropolitan areas. More than 1.7 million renter households and more than 5.3 million homeowner households are housed in these homes [7].

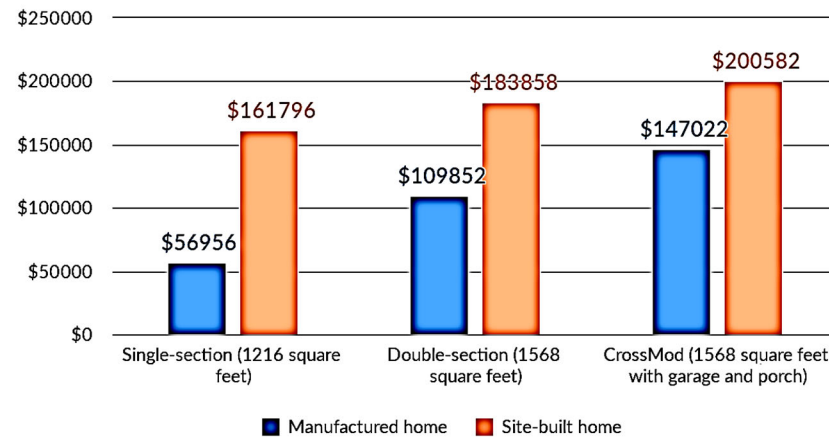


Figure 2. Cost comparison of different home types in 2020 [51].

Some manufactured housing units are located on property that belongs to the residents, while others are situated on rented lots in mobile home parks. These units are distributed over a variety of ownership arrangements. More than half of manufactured housing households own the land where their houses are situated, despite mobile home parks being linked to manufactured housing in popular narratives [11]. In mobile home parks, only 40% of households live on rented property. Low-income households' affordability and tenure security are significantly impacted by these various ownership arrangements, which emphasizes the need for more thorough comparisons across various tenure arrangements for manufactured housing. Therefore, manufactured homes make up a significant—yet little-researched—proportion of the affordable housing for urban and nonmetropolitan inhabitants. These figures unequivocally demonstrate how important manufactured housing is in increasing the number of low-income and minority households in the country who could become homeowners [7].

Table 1 presents manufactured home statistics for the U.S. over the past several years [8] and shows variations in key characteristics, including the number of homes inside and outside of communities, as well as their occupancy and foundation types. For example, the number of mobile homes inside communities has decreased from 19.1 thousand in 2019 to 16.5 thousand in 2020, while the number outside of communities has remained relatively stable, with a slight increase from 43.1 thousand in 2019 to 43.9 thousand in 2020. Occupancy data reveal a notable difference between homes with two or fewer occupants (10.9 thousand in 2020) and those with three or more occupants (49.6 thousand in 2020). The foundation types also reflect notable trends, with the number of homes on permanent masonry or concrete foundations seeing a steady increase, from 9.7 thousand in 2014 to 16.8 thousand in 2020, while homes with block piers and anchors/tie-downs have remained predominant throughout the years. The data underscore the dynamic nature of manufactured home ownership and its relationship to factors such as occupancy rates and foundation stability.

Table 1. Manufactured home statistics for the US (in 1000s) [8].

Mobile Home Statistics (in 1000s) in the US	2020	2019	2018	2017	2016	2015	2014
Inside communities	16.5	19.1	20.4	17.3	17.7	15.7	14.6
Outside communities	43.9	43.1	34.7	36.6	33.8	29.9	29.5
Personal property	47.2	47.1	42.2	40.7	39.8	36.6	35.3
On Real estate Land	11.7	12.0	9.2	9.2	8.5	6.5	5.8
Untitled Land	1.6	3.1	3.7	4.0	3.2	2.5	3.0
2 or less occupancy	10.9	13.2	10.4	10.5	10.4	8.4	7.3
3 or more occupancy	49.6	49.0	44.7	43.4	41.2	37.2	36.9
Permanent masonry or concrete foundation	16.8	15.9	12.9	10.5	10.5	9.2	9.7
Block Piers	36.1	38.4	35.9	38.1	35.2	32.2	26.2
Permanent masonry foundation	16.8	15.9	12.9	10.5	10.5	9.2	9.7
Anchors and Tie-down straps	43.4	45.8	41.9	43.2	40.9	36.4	34.3

Despite these benefits, manufactured housing has historically been seen as substandard [9,10], being frequently linked to energy inefficiency and poor building quality [52]. However, the quality of these homes was much enhanced in 1976 when federal building rules for manufactured housing were adopted. Compared to site-built dwellings, manufactured housing units are created in controlled factory environments that enable more reliable quality control and inspections. The stigma associated with manufactured homes and the communities that live in them endures despite these developments [10]. Many of the difficulties with manufactured homes are caused by problems with installation and infrastructure rather than flaws in the units themselves. For instance, according to the U.S. Census Bureau (2019), at least 10% of manufactured homes are not fastened to sufficient foundations, which makes them extremely susceptible to severe weather conditions like floods and strong winds [53]. The state of the infrastructure in communities of mobile homes varies greatly. While some towns, especially informal ones, lack even the most basic infrastructure, others have well-maintained roads, sewers, water systems, and power distribution [12]. This variation is partly because different states have different laws; some require frequent certification and inspections for these communities, while others only impose light regulation [54].

Furthermore, manufactured housing community residents are frequently put in risky financial and legal circumstances due to their tenure arrangements. One popular arrangement is the land lease, in which homeowners own their houses but rent the land from a landlord who manages the common areas and infrastructure. According to Desmond (2016) [55] and Sullivan (2018) [11], this system frequently exposes locals to exploitation through increased rents, dilapidated infrastructure, or the shutdown of entire towns. Even though these units are classified as mobile houses, homeowners' options are further limited because moving them is usually prohibitively expensive or logistically impossible. In most states, manufactured homes are categorized as personal property, or chattel, rather than real estate, which exacerbates these problems. Shorter loan periods, higher interest rates, and fewer lenders being willing to finance these items are frequently the results of this classification, which limits purchasers' access to financing choices [56,57]. These structural issues highlight the necessity of making changes to manufactured housing communities' infrastructure requirements, financial accessibility, and tenure security.

While manufactured housing is cost-efficient, it suffers from limitations such as repetitive designs, stigma, and reduced flexibility for customization. Additive manufacturing

offers a potential solution to these challenges. By enabling complex, aesthetic architectural elements, curved surfaces, and embedded insulation, AM can significantly elevate the design quality and thermal performance of manufactured homes. Furthermore, the transportable nature of 3D-printed components aligns well with modular factory-based production, enabling hybrid systems where AM is used to produce the core shell and manufactured housing processes complete the remaining interior and utility installations. This synergy can help reshape public perception while increasing scalability and design freedom.

Despite these challenges, manufactured housing remains a vital solution for providing affordable homes to low- and middle-income Americans, especially in areas where traditional housing options are too costly. However, as housing demands continue to grow, particularly for low-income households, there is a pressing need for more innovative and cost-effective solutions. One such solution lies in additive manufacturing (3D printing), which has the potential to revolutionize the construction of manufactured homes. By leveraging cutting-edge technologies, 3D printing can address many of the quality concerns, reduce construction costs, and enhance infrastructure in ways that traditional methods cannot. Moreover, this technology offers new opportunities to improve the affordability, sustainability, and scalability of manufactured housing, creating an exciting avenue for addressing the growing housing crisis.

In the following section, we will delve into the concept of additive manufacturing and explore how its application can transform the landscape of affordable housing by offering innovative solutions to longstanding problems in the construction industry.

2.3. Additive Manufacturing and Its Applications in Different Sectors

Additive manufacturing (AM), or 3D printing, refers to a family of technologies that create three-dimensional objects by successively adding material layer by layer, based on digital design models. Common AM techniques include fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), and extrusion-based concrete printing, each of which is suited to different materials and scales of application [3]. In the construction industry, extrusion-based systems where a gantry or robotic arm extrudes cementitious material are most relevant due to their ability to create large-scale, load-bearing elements without the need for formwork [4]. While this technology holds significant potential for improving cost-efficiency, reducing construction waste, and enabling mass customization, it also faces critical challenges. These include limited material options, inconsistent mechanical properties due to weak interlayer bonding, low thermal performance in monolithic prints, difficulty integrating reinforcement and MEP systems, and a lack of standardized codes and long-term durability data [5,6]. These technical and regulatory limitations hinder the widespread deployment of AM in mainstream construction. Acknowledging these barriers is essential for developing realistic strategies and pathways for AM adoption, especially regarding its application to affordable and socially impactful housing solutions.

Additive manufacturing (AM), also known as 3D printing, fundamentally alters how businesses think about their manufacturing processes, pushing them to reconsider where and how they conduct their operations. The ASTM F42 Technical Committee describes AM as a process in which materials are joined to form objects from 3D model data, typically layer by layer. This is in contrast to subtractive manufacturing methods, which involve removing material to create an object [58]. A variety of AM technologies are used in various industries, including fusion deposition modeling (FDM), stereolithography (SLA), selective laser melting (SLM), and selective laser sintering (SLS), among others. The materials used in AM range widely, including metals, ceramics, polymers, and composites, with each type of material being handled differently depending on the AM technology that is employed [59].

Being combined with other significant trends such as personalization, servitization, and presumption [60], AM is becoming a direct manufacturing process that promises to redefine global supply chains. A future that embraces shorter, more localized, and more sustainable value chains is emerging due to the widespread adoption of additive manufacturing and other advanced technologies [61]. By enabling the creation of goods layer by layer, AM mimics biological processes, which distinguishes it from traditional subtractive manufacturing methods, which are often wasteful and more resource intensive. AM provides a transformative advantage over traditional manufacturing processes, particularly regarding sustainability. One significant benefit is increased resource efficiency, as AM technologies help reduce waste during production and usage, optimizing material consumption throughout the product lifecycle [62]. Additionally, AM contributes to longer product lives by fostering more sustainable socio-economic patterns, such as improved connections between producers and consumers, and enables technical strategies like repair, remanufacturing, and refurbishing [62]. Furthermore, AM supports redesigned value chains, facilitating localized production, shorter supply chains, creative distribution strategies, and the formation of new partnerships, all of which contribute to a more sustainable and efficient economy [63].

While AM began as a tool for rapid prototyping and tooling, its application has expanded into direct production (Figure 3) thanks to improvements in its capabilities. Industries such as the aerospace industry, for instance, have fully embraced AM in producing highly complex components in limited quantities [59,64]. The medical sector also utilizes AM to create customized products such as prosthetics, implants, and hearing aids [65]. This trend illustrates the potential for AM to meet the growing demand for highly specialized, one-off goods in sectors that require customization. As AM technology continues to evolve, other advancements in cold spray-based AM processes have emerged, which are now being marketed as part of the AM landscape despite not being traditionally viewed as such [66].

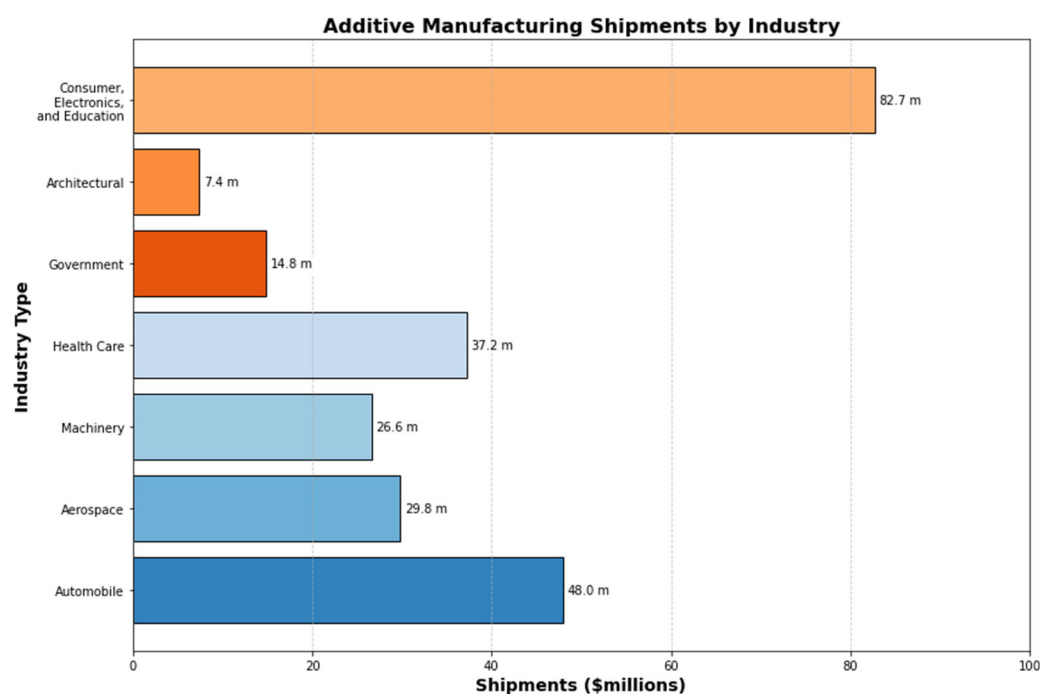


Figure 3. Additive manufacturing shipments by industry [67].

Alongside these industrial advancements, the consumer-grade 3D printing market has flourished. Home 3D printers, such as those based on FDM technology, have become increasingly accessible. These printers, which grew in popularity following the expiration of

patents and the rise of open-source movements, allow individuals to create and customize products on demand, empowering consumers to participate in the manufacturing process in new ways [68]. With these technological and commercial developments in mind, it can be seen that the potential of AM extends beyond traditional manufacturing sectors. Given its capability to reduce costs, minimize waste, and enhance sustainability, AM presents a unique opportunity to revolutionize industries that are heavily dependent on large-scale, resource-intensive production processes, such as housing construction. In the next section, we will discuss the potential of additive manufacturing technology to transform the housing affordability landscape.

2.4. Technical Challenges and Systemic Constraints in AM for Construction

To enhance the practical relevance of this review, this section provides a focused discussion on the specific technical and systemic challenges currently limiting the application and scalability of additive manufacturing (AM) in the construction industry. Despite its promising potential, AM-based construction faces a number of material, regulatory, operational, and implementation hurdles that must be addressed before it can be widely adopted in affordable housing development [5,6].

One of the foremost technical barriers is material selection. Most commercially available printable materials—particularly those for extrusion-based concrete printing—are proprietary, expensive, and lack standardized performance data across regions [5]. These mixes often require highly controlled environments and precise calibration, which limits their adaptability to varying climatic and site conditions. Furthermore, structural integrity concerns have arisen regarding the layer-by-layer deposition process, which introduces anisotropic behavior and weak interlayer bonding. These characteristics reduce the load-bearing capacity and long-term durability of printed components, especially when they are under seismic or environmental stress [6]. Another critical limitation is thermal performance. Unlike traditional wall systems that include insulation layers or cavities, most 3D-printed walls are monolithic and lack thermal breaks, which thereby compromises the energy efficiency of the built structure [16].

Beyond the structural envelope, AM workflows are currently not well integrated with mechanical, electrical, and plumbing (MEP) systems. Embedding or accommodating utilities in 3D-printed components remains a challenge, often requiring time-consuming and costly post-processing [4]. Additionally, logistical constraints associated with large-scale deployment—such as the limited mobility and large footprint of gantry-based or robotic printing systems—restrict the practical implementation of AM on uneven terrain or in dense urban environments [69].

At the systemic level, building code adaptability is a major bottleneck. Most national and municipal construction codes are not yet designed to accommodate non-traditional geometries, unconventional layer-based construction methods, or the novel materials used in AM. This creates significant delays in permitting and increases uncertainty for developers, regulators, and investors. Finally, the feasibility of mass production remains limited. Current AM technologies suffer from low throughput, extended printing times, and a lack of automation in reinforcement placement, surface finishing, and utility integration [4,69]. Unlike conventional prefabrication techniques that support high-volume, factory-based housing production, AM still lacks the production efficiency required to scale it for large affordable housing developments.

Taken together, these challenges, spanning material science, structural performance, regulatory frameworks, digital integration, and manufacturing efficiency, highlight the substantial work that is still needed to transition AM from experimental use to mainstream, scalable application in the housing sector. Addressing these issues through targeted

research, standardization, policy reform, and investment in system-level automation will be critical to unlocking AM's transformative potential in addressing the global affordable housing crisis.

2.5. Representative Case Studies of AM in Architectural Applications

To address the diversity and architectural implications of additive manufacturing (AM) technologies, this review has been enhanced by the incorporation of representative case studies that demonstrate how different AM methods are being applied in real-world construction settings [21]. One notable example is the ICON 3D-printed community homes in Austin, Texas, where the proprietary *Vulcan* extrusion-based concrete printing system was used to build single-family homes for low-income families. These homes are designed with integrated wall insulation and were printed in under 48 h, with up to a 60% reduction in material waste and a 30% reduction in construction time being achieved compared to conventional methods [2]. The project illustrates how gantry-style AM systems can be deployed for the manufacture of scalable, repeatable housing models that are tailored for affordability and sustainability.

Another exemplary case is the Habitat for Humanity 3D-printed house in Williamsburg, Virginia, where the *Alquist 3D* system was used to construct a 1200-square-foot home. The project demonstrates a hybrid construction model that integrates 3D-printed concrete walls with conventional roofing and interior components. It also emphasizes practical outcomes such as permitting, energy efficiency, and public acceptance [21]. A more technologically advanced example is the Dubai Municipality project, which produced a two-story office building using a robotic arm-based printing system developed by Apis Cor. As one of the world's tallest AM structures to date, this project showcases the architectural flexibility of mobile robotic arms in printing multi-story and geometrically complex structures without the constraints of a gantry frame [70–74].

This structure was built in a hot-arid climate, which demonstrated not only height and complexity but also thermal resistance [75]. Additionally, the MX3D bridge in Amsterdam was built using WAAM in a temperate maritime climate, which highlights the technology's adaptability to different environmental conditions [76]. Finally, the Winsun multi-story building in China was built using recycled concrete in a humid subtropical zone, which confirms AM's potential in both commercial and high-humidity contexts [71].

These diverse case studies not only highlight the unique capabilities of various AM platforms—gantry, robotic arm, and hybrid systems—but also underscore their impacts on material efficiency, construction speed, and design flexibility in architectural practice. They offer valuable insights into how AM is moving beyond prototypes toward practical, code-compliant building systems.

2.6. Advanced Collaborative and Robotic Printing Applications

To provide greater depth and global relevance, this review has been expanded to include real-world architectural applications of large-scale robotic and collaborative additive manufacturing (AM) systems. One of the most pioneering examples is the Technical University of Munich's "3D Printed Bridge", which was built in Germany by using an autonomous mobile robotic arm system to fabricate a full-scale pedestrian bridge out of composite materials. The project demonstrated the use of synchronized robotic printing arms operating in real time with minimal human intervention, highlighting the potential of robotic swarm fabrication to revolutionize structural formwork and architectural complexity [73,74,77]. Similarly, in China, the Winsun project utilized a gantry-style collaborative 3D printing system to build a multi-story apartment structure using a recycled concrete mix, showcasing scalability, material reuse, and structural feasibility in a dense urban con-

text [69]. These examples illustrate how robotic and multi-agent printing systems are being developed to improve the speed, scale, and geometric freedom of 3D-printed buildings.

Further advancing this trend, the MX3D bridge in Amsterdam, created using a six-axis robotic arm and metal wire arc additive manufacturing (WAAM), offers another landmark case. This stainless-steel pedestrian bridge, printed in situ over a canal and later fitted with structural monitoring sensors, reflects how robotic AM can integrate architectural design with real-time data feedback, an essential feature for smart infrastructure [78–81]. In the Middle East, the construction of Dubai Municipality’s AM building, the largest 3D-printed structure by volume at the time of construction, employed Apis Cor’s robotic arm printer, which enabled offsite construction followed by onsite assembly. This project illustrated the feasibility of deploying mobile printing systems in hot desert climates while navigating regional regulatory requirements [71]. Collectively, these international case studies offer advanced practical scenarios that reveal not only the versatility of AM in architectural design but also the regional adaptations and scientific developments that underpin its global deployment.

3. Case Study: AM vs. Traditional Housing Construction by Habitat for Humanity, Virginia

In 2021, Habitat for Humanity partnered with Alquist 3D to build a 1200 sq. ft. single-family home using a gantry-based concrete 3D printer. The project completed exterior wall construction in just 28 h, cutting the estimated build time by 20% and material waste by over 50% compared to conventional stick-built methods. The overall construction cost was approximately \$174/sq. ft., in contrast to the local market average of \$200–\$225/sq. ft., which illustrated early-stage but measurable cost-efficiency. The hybrid approach combining 3D-printed walls with traditional roofing and interior systems demonstrates how AM can complement, rather than replace, legacy systems in affordable housing delivery [21].

In addition to the Habitat for Humanity case, other projects have demonstrated AM’s potential in different geographies. For instance, ICON’s East 17 community project in Austin, Texas demonstrated a scalable approach using 3D-printed wall systems for affordable housing, achieving build times that were under 48 h [2]. Similarly, Bazli et al. (2023) [81] examined the use of AM in remote housing, identifying up to a 30% reduction in logistics and labor costs, which is particularly relevant in rural applications.

Table 2 shows a side-by-side comparison of a traditional stick-built home and a 3D-printed home built by Habitat for Humanity using the Alquist 3D system. The data demonstrate cost, time, and waste savings that were enabled by AM, while also showing that hybrid approaches still rely on traditional components like roofing and interiors.

Table 2. Comparison of a traditional stick-built home and a 3D-printed home built by Habitat for Humanity.

Metric	Traditional Build (Virginia, USA)	3D-Printed Home (Habitat/Alquist 3D)
Total Area (sq. ft.)	~1200	~1200
Wall Construction Time	1–2 weeks	28 h
Average Cost per sq. ft.	\$200–\$225	~\$174
Estimated Waste Reduction	Baseline	~50–60%
Method	Wood framing, drywall	Extruded concrete, hybrid finishing

While AM offers several construction benefits, it remains constrained by limitations in material behavior and system maturity. The anisotropic nature of layer-by-layer printing leads to weaker interfacial bonding, which compromises the resulting structural integrity

compared to monolithic or reinforced concrete structures [6]. Additionally, the limited material diversity, particularly in printable composites and bio-based alternatives, restricts design flexibility. Unlike traditional construction, which accommodates a wide range of reinforcements, most AM systems lack the ability to effectively integrate steel without post-processing. Data on the durability of 3D-printed structures under environmental loading (freeze–thaw, moisture ingress, seismic activity) are also scarce, and few long-term studies exist to validate their lifecycle performance. These material uncertainties highlight the importance of further empirical validation of these methods prior to their full-scale regulatory adoption. Table 3 summarizes the key differences between traditional construction and additive manufacturing across performance, cost, and sustainability metrics.

Table 3. Comparative analysis of key technical differences between AM and traditional manufacturing in the construction industry.

Category	Additive Manufacturing (AM)	Traditional Manufacturing (TM)
Structural Integrity	Layer anisotropy, weak interlayer bonds	Monolithic casting or framing, predictable performance
Material Diversity	Limited printable options, proprietary mixes	Wide range of cementitious and composite options
Reinforcement Compatibility	Post-processing often required; limited real-time integration	Reinforcement embedded during casting/formwork
Regulatory Support	Sparse code recognition, pilot-level status	Well-established in all jurisdictions

4. Potential of Additive Manufacturing to Transform Housing Affordability Landscape

While AM offers significant promise in reducing labor, formwork, and material waste, these benefits often mask the high initial capital investment required for equipment, proprietary materials, and workforce training. For example, although ICON’s homes in Texas demonstrate 30–50% reductions in build time, the overall cost-effectiveness remains contingent on the scale, repeatability, and supply chain proximity. Current data suggest that AM becomes economically competitive primarily in repetitive, modular housing typologies or in regions with high labor costs. Future studies should apply lifecycle cost analysis and breakeven modeling to assess where AM offers a genuine economic advantage for affordable housing.

There are many benefits to employing 3D printing in the housing industry. Because of its accuracy, a 3D printer can, when properly optimized, cut construction waste by from 30% to 60% compared to conventional methods [70]. Additionally, the automated 3D printing process lowers labor costs—which usually account for over half of the costs in traditional housing projects—by from 50% to 80%, eliminating the need for on-site workers [71]. Furthermore, the system’s design flexibility removes the requirement for formwork, which shortens project durations and lowers costs, especially for housing projects that involve concrete buildings. According to Ma et al. (2018) [4], the cost of formwork usually accounts for between 35% and 60% of the total cost of concrete structures. This removal makes the use of custom structural components possible, which further lowers the cost of building new homes.

To illustrate the global cost dynamics of the use of AM in construction, Figure 4 includes regional data from Middle Eastern projects, which serve as a benchmark for emerging economies with similar housing needs.

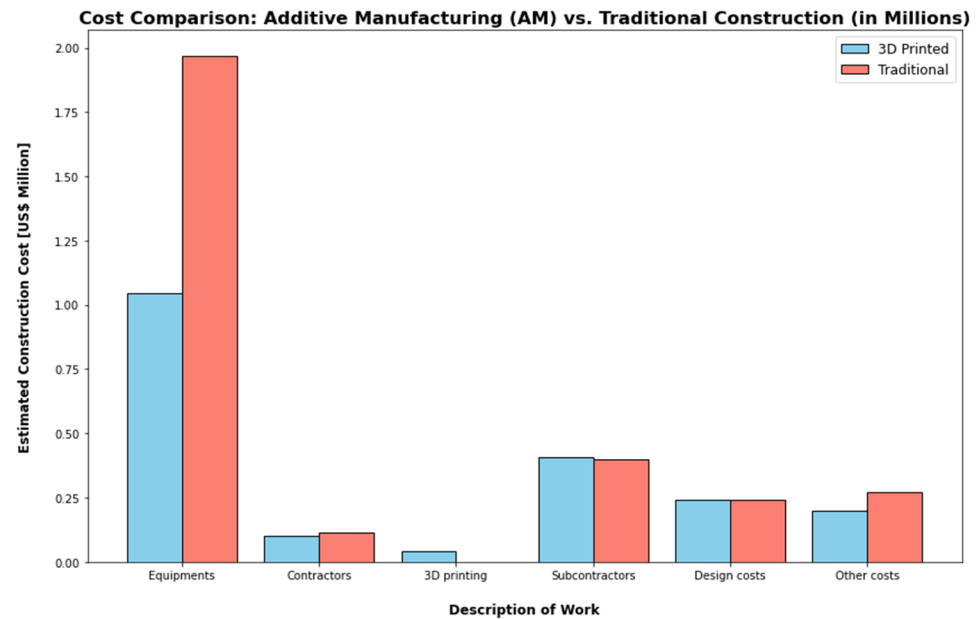


Figure 4. Cost comparison of AM and traditional construction in the Middle East [71].

The cost data presented in Figure 4 are derived from regional studies that were conducted in the Middle East, where comparative assessments of conventional and additive manufacturing (3D printing) construction methods were performed. The *x*-axis reflects construction techniques, including 3D printing, which are used as a benchmark for evaluating relative the cost-efficiency and schedule performance in pilot projects.

According to Kreiger et al. (2019) [72], 3D-printed construction is 10–25% more cost-effective than buildings made of concrete masonry units and 25–37% less expensive than cast-in-place construction. This is mainly because formwork expenditures are eliminated. 3D printing significantly improves the buildability, flexibility in construction, and architectural adaptation of building construction [73,74,77]. With the use of lean construction concepts, this advancement has the potential to result in a notable 60% decrease in design time [73]. These principles include task standardization and ongoing process improvement to expedite and eliminate inefficiencies in the construction process. This technology's buildability and architectural flexibility help to reduce costs and speed up home design and prototyping (Figure 4), directly cutting down on housing delivery times by 55% [78].

Even though 3D printing has several advantages, such as lower labor and formwork costs, waste reduction, quicker production schedules, and greater flexibility and adaptability during the design and construction stages, it is essential to consider how it affects carbon emissions. About 20% of a 3D-printed home's carbon emissions come from the 1.5–2 times more Portland cement used in 3DPC than traditional casting, which significantly raises the amount of carbon embodied in the used materials [79,80]. Research has investigated ways to reduce the carbon footprint of materials used in 3D printing. Entirely substituting recycled concrete aggregate for virgin aggregate in 3DPC has been found to have a negligible impact on lifetime carbon emissions, accounting for around 2% of possible global warming [79]. Researchers have studied alternative materials and mixes to improve sustainability. According to a study by Mohammad et al. (2020) [80], the carbon footprint of 3DPC can be decreased by more than 70% by adjusting the concrete mixtures used for 3D printing with fly ash and nanofibers. Furthermore, it has been shown that using geo polymers instead of regular Portland cement reduces greenhouse gas emissions by 80% compared to typical cement manufacturing [81].

According to studies looking at the energy consumption and carbon emissions that occur during the building process of 3D printing, 3D printer activities only contribute

2% of the total lifecycle emissions of 3DPC homes [75,82]. The fact that this electricity is frequently derived from renewable and environmentally favorable sources makes it a more environmentally friendly choice. In comparison, the carbon emissions caused by traditional housing construction, which are mainly derived from fossil fuel sources, account for 2–5% of the house's total lifecycle emissions [76]. Researchers have estimated that 3D-printed houses could potentially reduce the environmental impact of housing projects by up to 50%, although a thorough whole-lifecycle assessment for an actual 3D-printed house has not been conducted. This is primarily because conventional methods require significantly more energy to manufacture products than 3D printing ones, which require from 41% to 64% less energy [61].

To summarize the benefits of 3D-printed homes over traditional timber-based and light steel frame (LSF)-based homes, Figure 5 presents a spider plot comparing the global warming potential (GWP) across different lifecycle stages, as reported by Khan et al. (2024) [76], for various home types in New Zealand. Figure 5 highlights that 3D-printed homes generally have a lower GWP compared to LSF- and timber-based homes, particularly in the production and construction stages. 3D-printed homes show a lower GWP in material production and construction processes, while timber homes are slightly more efficient than LSF homes. All three home types show similar GWP values in their maintenance and life stages, but 3D-printed and timber homes exhibit benefits in material recycling at the end of their life, with LSF homes showing the highest negative GWP in the beyond-system-boundary stage. It is clear from this plot that 3D-printed homes are more sustainable, offering a reduced environmental impact, particularly in the early stages of their lifecycle, compared to traditional building methods.

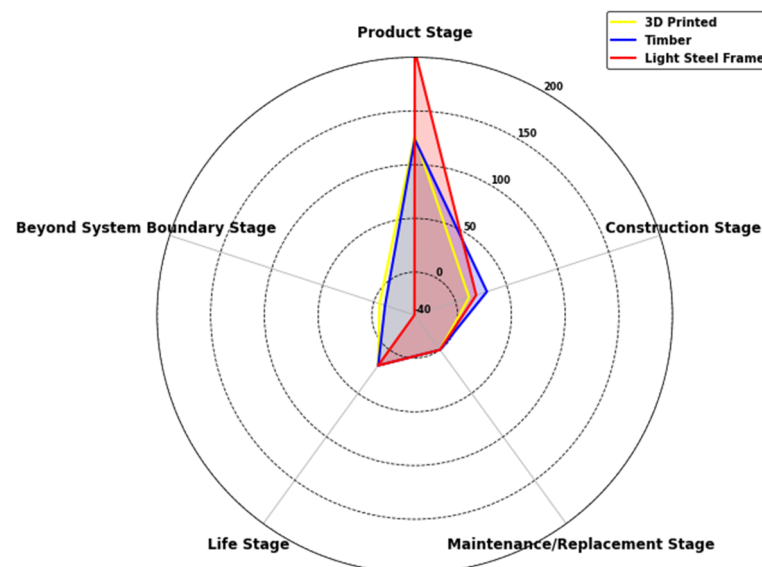


Figure 5. Global warming potential (kgCO₂eq/m²) for different housing types [79].

Although the expenses of labor, equipment, scaffolding, and formwork are significantly reduced for 3D-printed homes, and these homes exhibit an average of 40% reduction in material waste, the cost of materials for 3D printing is higher than that of traditional and locally available materials. The primary reason for this is that the materials used in 3D printing today are either created in labs or are only made by a select few 3D printing businesses, which makes them proprietary materials. Because 3D printing materials are expensive, the building costs of 3D-printed homes are higher than those of conventional housing projects. For example, because 3D printers employ a fine-grained, high-strength concrete mixture, the average cost of cementitious 3D printing materials increased by 80%,

according to Nodehi et al. (2022) [83], and the cost of concrete materials increased by 70%, according to De Schutter et al. (2018) [5]. The lack of a thorough LCC makes it more difficult to estimate the total cost of 3D-printed homes accurately compared to traditional methods. Nonetheless, the general opinion among academics indicates that, particularly when considering low-income and subsidized housing, the present cost of 3D-printed homes is anticipated to be higher than that of conventional homes [84,85].

The number of units, complexity, and cost of each unit for both traditional and 3D-printed projects were examined in a study by Ma et al. (2018) [85] that examined economies of scale and the breakeven for 3D printing technology in the construction industry. According to their data, the cost of 3D printing is mainly constant for every production unit, with only minor variations depending on the overall quantity and complexity. In contrast, the cost per unit rises with the complexity in conventional projects. However, the cost per unit decreases with each additional production unit and with the total number of building objects. Therefore, 3D printing is ideal for moderately complex projects like mass housing projects and low-to-medium-sized building projects. Despite its many positive effects on the economy, society, and environment, 3D printing has disadvantages, just like other technologies. Overall, the primary disadvantage of 3D printing systems is their high initial cost, which can significantly deter the adoption of these methods, especially for projects that involve inexpensive housing, where cost-effectiveness is essential [72]. However, construction project costs are anticipated to gradually decrease as technology adoption rates and 3D printing throughput improve in the years to come. The rapid development of bio-mediated geomaterials for 3D printing in construction will expedite the cost reduction of 3D printing, being driven by growing use and technological improvements.

Despite promising pilot demonstrations, several operational challenges limit the widespread adoption of AM in affordable housing. The material supply chain for printable concrete is not yet mature, and most products are proprietary or available only through select vendors. Additionally, there is a significant workforce gap, as traditional construction laborers typically lack training in digital modeling, AM hardware, and software integration. Compounding this is the fragmented nature of building codes: most jurisdictions lack clear permitting pathways for 3D-printed structures. Without coordinated policy and training programs, these gaps could delay AM's mainstream adoption. Pilot projects should prioritize working with local governments to develop permitting templates and certification frameworks.

5. Future Directions and Research Priorities

While additive manufacturing (AM) has shown transformative potential for sustainable and affordable construction, significant research gaps remain that limit its widespread implementation. Based on our review of current technologies and case studies, we identify the following areas as critical for future investigation:

1. **Standardization and building codes:** The lack of formal codes and certification procedures for AM-constructed structures remains a fundamental barrier. Future work should focus on developing standardized design, material testing, and performance evaluation protocols that are compatible with regional and international building regulations;
2. **Long-term durability and performance:** There is a notable absence of long-term field data on the mechanical, thermal, and environmental performance of 3D-printed structures, particularly under real-world aging, loading, and climatic conditions. Research should target durability testing and lifecycle assessments (LCAs) for various AM materials and assemblies;

3. Integration with digital design and AI systems: Emerging tools such as digital twins, generative design, and AI-based optimization algorithms can enhance the customization, monitoring, and adaptive reconfiguration of AM-based construction. Future studies should explore the interoperability of AM with these advanced digital frameworks to improve design precision and operational efficiency;
4. Social acceptance and financing mechanisms: Despite technical progress, public skepticism regarding the quality and permanence of AM-constructed homes persists. Additionally, financing options for AM projects remain underdeveloped. Interdisciplinary research involving sociology, economics, and urban planning is needed to address the public perception, housing policy integration, and innovative funding models regarding 3D-printed construction;
5. Scalability and automation of full construction workflows: Although AM has demonstrated success in printing walls and shells, the integration of reinforcement, mechanical–electrical–plumbing (MEP) systems, and surface finishing into an automated workflow remains a technical and logistical challenge. Future research must address multi-material printing, robotic coordination, and end-to-end automation to enable true scalability.

By addressing these unresolved questions, future research can help bridge the gap between the experimental demonstration and the large-scale implementation of AM technologies in the built environment, particularly in the context of affordable housing.

To scale the integration of AM with manufactured housing to allow for more affordable housing, coordinated policy interventions are essential. Policymakers should consider: (1) developing national and regional standards for AM materials and structural performance; (2) offering tax incentives or innovation grants for developers using certified AM systems; (3) funding workforce retraining programs through technical colleges or unions; and (4) supporting public–private pilot housing projects that integrate AM technologies. Successful examples such as Dubai’s 3D-printed building code initiative and HUD’s Innovation Housing Showcase demonstrate how regulation and innovation can align to overcome barriers and accelerate real-world implementation.

This review is limited by the scarcity of long-term empirical studies on 3D-printed buildings, particularly in the areas of operational energy use and maintenance performance. Moreover, much of the cost data are derived from early-stage pilot projects, which may not be generalizable. Geographic bias toward examples from the global north also limits applicability to developing contexts.

6. Conclusions

The global affordable housing crisis remains one of the most pressing issues of the 21st century, and is worsened by rapid urbanization, rising income inequality, and a stagnating housing supply. The demand for affordable housing has outpaced the supply, particularly in rapidly urbanizing regions of the global south and certain developed areas. Housing affordability continues to present a significant barrier to equitable urban development. This paper contributes to the ongoing discourse on affordable housing by exploring the complementary role of manufactured housing and additive manufacturing (AM) technologies. By analyzing the strengths and challenges of both technologies, this paper identifies a need for their integration to address key issues such as construction speed, cost, sustainability, and social acceptability. The aim is to provide a comprehensive perspective on how these technologies can be used in tandem to not only alleviate housing shortages but also improve the quality and environmental performance of housing for low-income populations.

Traditional housing models, such as public housing and subsidies, have proven inadequate, leading to the exploration of alternative solutions, including manufactured

housing and additive manufacturing (AM) technologies. Manufactured housing has been a key part of affordable housing for decades. However, barriers such as negative public perception, quality concerns, and financing challenges persist. Despite these issues, manufactured homes remain attractive due to their cost-effectiveness, construction speed, and modularity, especially in suburban and rural areas where land is more affordable. Innovations in construction techniques and design have addressed many stigmas, focusing on energy efficiency, durable materials, and aesthetic improvements. Yet, financial models that treat manufactured homes as personal property, rather than real estate, result in higher borrowing costs and hinder investment in infrastructure. A more consistent regulatory and financial framework could significantly improve the role of manufactured housing in solving the affordable housing crisis. Table 4 presents real-world examples of AM-based projects across various building types and climate zones.

Additive manufacturing, specifically 3D printing, represents a promising technological innovation with the potential to transform housing construction. Technologies like 3D concrete printing offer benefits over traditional methods, including reduced material waste, faster build times, and the ability to create complex structures with less labor [10]. Early trials suggest that 3D printing could reduce construction costs and time costs, offering affordable, sustainable housing solutions. However, challenges such as the high cost of 3D printing machines, limited material availability, and regulatory obstacles remain. Table 4 presents more details on the advantages and disadvantages of using 3D printing technology in the housing sector [82]. While 3D printing can reduce construction waste and carbon emissions, more research is needed to identify the most sustainable materials. Integrating manufactured housing with 3D printing offers a promising solution to several challenges in the affordable housing sector, combining the scalability and cost-effectiveness of manufactured homes with the technological advantages of additive manufacturing. This integration can result in customizable, environmentally sustainable, and affordable homes. For instance, 3D printing can be used to produce modular components that are easy to assemble on-site, significantly reducing construction time and costs. Moreover, the use of sustainable materials such as recycled plastics or eco-friendly concrete in the 3D printing process could further enhance the environmental performance of these homes, contributing to more sustainable housing solutions. The reduction in labor costs and the streamlining of the construction process result in significant cost savings, which can make housing more accessible to those who need it most. The potential for mass customization through 3D printing also means that homes can be designed with specific local needs in mind, which allows for a level of personalization and flexibility that traditional construction methods cannot easily achieve.

This review contributes to the literature by providing a comprehensive synthesis of additive manufacturing applications with affordable housing and their integration with manufactured housing, offering both technical and policy-oriented insights. Unlike existing reviews, this paper bridges architectural, regulatory, and social dimensions, and offers a case-supported analysis of scalability potential. The review also outlines realistic research and implementation pathways, helping policymakers and engineers identify where AM is most viable.

The future of affordable housing requires a collaborative, interdisciplinary approach that integrates insights from urban planning, technology, economics, and social policy. A critical gap remains in the integration of various housing solutions, such as manufactured homes and 3D printing, within a cohesive policy framework that addresses land tenure, financing, sustainability, and equity. While this paper does not provide a detailed policy framework, it suggests key principles for the integration of manufactured housing and 3D printing within affordable housing strategies. Policies that encourage advanced manu-

facturing technologies in affordable housing construction are needed, alongside efforts to ensure these solutions meet the social and economic needs of low-income communities.

Governments and private developers must also create financing models to ensure that these technologies are accessible to vulnerable populations. Addressing public perceptions of new housing technologies is crucial. Manufactured homes, often seen as substandard, face stigma that limits their adoption. Public education campaigns that promote high-quality designs could help shift opinions and build broader support. For 3D-printed homes, proving their durability and safety through rigorous testing and demonstration projects will be essential to gain public confidence. Ongoing research into sustainable materials for both manufactured and 3D-printed homes is also critical. Low-cost high-performance composites could enhance the durability and energy efficiency of manufactured homes. Similarly, alternative materials such as recycled concrete or bio-based composites could improve the sustainability of 3D printing [78].

Table 4. Advantages and disadvantages of additive manufacturing for housing [82].

Aspect	Advantages	Drawbacks
Technical	- Enhances flexibility, adaptability, and overall buildability in construction projects. - Speeds up design and construction processes, reducing time by 60–90%. - Provides more freedom in designing intricate and complex structures that would be challenging with traditional methods.	- Requires basic training and a certain level of digital skills to operate effectively. - The range of available materials is limited, and some may be proprietary. - There is a lack of established building codes and regulations specific to 3D printing techniques and materials.
	- Enables mass production and customization, allowing for personalized designs on a large scale. - Reduces human error and improves accuracy in the final product. - Allows construction in locations that are difficult to access or pose hazards to workers.	- It is not yet feasible to print entire buildings or projects using 3D printing. - There are size limitations on the structures that can be printed. - Some 3D printing materials might not possess the strength or durability required for certain traditional construction standards.
Economics	Significantly lowers labor costs (by 50–80%).	Proprietary or laboratory-produced materials can be much more expensive (by 50–80%).
	- Cuts down on the need for formwork, which can account for 35–60% of concrete construction costs. - Helps minimize material waste, reducing it by around 40%. - Eliminates costly errors and rework, leading to fewer defects and re-doing of tasks. - Enables mass production, further driving down overall construction costs. - Reduces transportation costs by eliminating the need to transport large, prefabricated components.	- The initial setup and investment costs can be quite high. - The upfront costs for 3D printing materials and equipment can make it less affordable for smaller-scale projects.

Table 4. Cont.

Aspect	Advantages	Drawbacks
Environmental	- Contributes to reducing carbon emissions during the construction process. - Using locally sourced, bio-based materials can further decrease the carbon footprint. - Improves energy efficiency of buildings during operation, reducing carbon emissions. - Offers opportunities to use sustainable and recycled materials for construction.	Some 3D printing materials, particularly cement-based ones, can increase the embodied carbon in the finished structure by up to 20%.
	- The use of renewable energy sources during the 3D printing process further reduces the carbon footprint by eliminating fossil fuel use. - Less transportation is required for large components, helping to reduce associated emissions.	
Social	- Can lead to improved quality of life for residents and users by delivering high-quality, customized structures. - Promotes local employment opportunities by offering short training periods for new workers. - Creates safer and more sustainable job opportunities both on-site and off-site. - Facilitates the reskilling and upskilling of workers, enabling them to transition into more advanced roles within the industry.	- The shift to 3D printing may reduce the number of low-skilled jobs traditionally created in the construction industry. - The overall number of new jobs generated in the community may be limited compared to traditional construction methods. - Some users may be hesitant to accept 3D-printed buildings due to concerns about the appearance or rough finish of the structures.

Additionally, scaling 3D printing for mass housing production will require breakthroughs in printing speed, material strength, and cost reduction. Regulatory frameworks must adapt to accommodate new construction technologies. Current building codes often do not address the unique characteristics of 3D-printed homes, such as the materials used and the construction process. Updating building codes will be necessary to ensure safety while promoting innovation. Manufactured housing standards must also reflect advances in technology and design while keeping manufactured houses affordable for low-income buyers. The affordable housing crisis demands innovative, scalable solutions that integrate both traditional and emerging technologies. Manufactured housing and 3D printing offer promising paths forward, but overcoming technical, financial, regulatory, and social barriers is essential. Policy frameworks need to evolve to support these technologies and ensure that they meet the social and economic needs of low-income communities.

Governments must work with private developers to create financing models that make these technologies accessible, while also addressing public perceptions of manufactured and 3D-printed homes. Educational initiatives can help shift public opinion by demonstrating

the benefits of high-quality designs and durable, safe construction. Furthermore, regulatory frameworks must adapt to accommodate new materials and building processes, ensuring safety while promoting innovation. Future research should focus on advancing materials and construction methods, alongside the development of policies and financing models that support low-income populations. If these efforts are pursued with sustained commitment, manufactured housing and 3D printing could play a pivotal role in alleviating the global affordable housing crisis.

Despite these findings, this study is constrained by a limited global dataset and reliance on pilot-scale outcomes. Continued field validation and broader climate-region studies are needed to confirm AM's full potential across building typologies.

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