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Additive manufacturing in construction: bridging innovation and sustainability

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Abstract

Additive manufacturing (AM) is rapidly transforming the construction industry by introducing new possibilities in design, sustainability, and cost efficiency. This review explores the latest developments in AM technologies, materials, and real-world applications, with a particular focus on case studies that demonstrate AM's practical value. Key techniques such as fused deposition modeling, binder jetting, and shotcrete 3D printing are examined for their ability to produce complex architectural forms, reduce construction time, and minimize material waste. Case studies—including the YHNOVA project in France, the Office of the Future in Dubai, the MX3D Bridge in Amsterdam, ICON's 3D-printed homes in Mexico, COBOD's infrastructure in India, and Indonesia's MODULA 3D project—highlight the growing global relevance of AM across residential, commercial, and public sectors. In addition, this paper reviews emerging innovations such as multi-material printing and the use of sustainable alternatives like geopolymer concrete. While AM presents clear benefits, its wider adoption faces challenges related to regulatory standards, technological scalability, and material limitations. This review concludes that with continued research and cross-disciplinary collaboration, AM holds strong potential to enable more sustainable, affordable, and innovative construction solutions worldwide.

Keywords: *additive manufacturing, construction industry, sustainable building, geopolymer concrete, multi-material printing*

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1. Introduction

Additive manufacturing (AM) has gained significant attention in recent years due to its potential to revolutionize the construction industry. This technology allows for the layer-by-layer fabrication of structures directly from digital models, offering distinct advantages over traditional construction methods, such as design flexibility, material efficiency, and cost reduction. Originally utilized for prototyping in industries like aerospace and automotive, AM is now being explored for its applications in building construction, where the need for more sustainable and efficient practices is critical [1, 2].

The construction industry faces numerous challenges, including high material waste, energy consumption, and environmental impact. Traditional construction methods often result in significant resource inefficiencies, making it essential to seek innovative solutions that can address these issues. AM has been proposed as a promising alternative that not only reduces material waste but also enables the creation of complex architectural designs that would be costly or impossible to achieve through conventional methods [3, 4]. Furthermore, AM allows for on-site production, reducing transportation costs and enhancing the sustainability of construction processes [5].

However, the integration of AM into mainstream construction practices faces several hurdles. These include material limitations, regulatory challenges, and difficulties in adapting current construction workflows to accommodate AM technologies. Current research focuses on overcoming these challenges by improving AM processes, optimizing material usage, and exploring innovative approaches such as multi-material printing and the use of sustainable materials like geopolymer concrete [6, 7].

Despite recent reviews covering the fundamentals, applications, and challenges of AM in construction, this paper identifies a gap in understanding the integration of AM into practical workflows. While reviews have been published in the past two years, few focus on the intersection of scalability, material limitations, and workflow integration. This review addresses this gap by critically examining the latest advancements and identifying key trends, such as the incorporation of AI in AM, which remains underexplored in the current literature.

The objective of this review is to examine the current state of AM in the construction industry, analyze its benefits and limitations, and explore potential pathways for its broader adoption. By evaluating existing technologies and recent innovations, this paper aims to provide insights into how AM can address critical challenges and contribute to a more sustainable future for the construction sector.

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2. Fundamentals of additive manufacturing

In additive manufacturing, the desired component is built up step-by-step from a digital 3D model through the targeted application of material. In contrast to conventional processes, additive manufacturing offers both technical and economic advantages:

-Additive manufacturing enables the development of complex geometric component structures that cannot be achieved using conventional methods.

-With conventional methods, costs and time expenditure can increase exponentially with increasing component complexity. This is not an issue with additive processes.

-Customized products and small batches can be produced much more cost-effectively.

-Individual customization to the customer's wishes is possible without much effort.

-Much shorter time-to-market can be achieved thanks to production without tools [1].

For this reason, additive manufacturing is increasingly recognized as having disruptive potential, as its specific manufacturing process means that it is not based on conventional manufacturing processes but instead covers a completely new approach to the production of goods [2].

Additive manufacturing can be divided into three areas of application: rapid prototyping, rapid tooling, and rapid manufacturing.

Rapid prototyping refers to the rapid production of models that serve as prototypes. This means that there is no need to manufacture tools or fixtures using additive manufacturing, which saves both time and money. The model can be created overnight as only the previously created CAD file is required. This means that the product can be inspected and tested the very next day. As prototypes are no longer the only thing being produced today, the term rapid prototyping is no longer appropriate. For this reason, the umbrella terms “additive manufacturing” and “3D printing” have been agreed upon [3].

In rapid tooling, tools and molds are produced using additive manufacturing processes. The resulting product must fulfil the same quality requirements as a similar mold produced using a subtractive process (drilling, milling, or turning). One advantage of rapid tooling is that cooling channels can be specifically integrated into the mold using the 3D printer. This increases the service life of the product and is difficult to achieve with conventional manufacturing processes [4].

Rapid manufacturing is the production of ready-to-install components and end products using 3D printing. The focus here is on the fastest possible development and implementation of components without the use of support molds or tools [5].

The potential applications of additive manufacturing processes for the production of end products span a wide range of industries, including mechanical engineering, automotive, automation, aerospace, electrical engineering, medicine, architecture and construction, fashion, textiles, toys, food, and defense materials [1]. This broad applicability emphasizes the flexibility and transformative potential of additive manufacturing.

In the construction industry in particular, AM technologies such as fused deposition modeling (FDM), selective laser sintering (SLS) and stereolithography (SLA) are opening up new possibilities. These technologies make it possible to address specific challenges in the industry through the adaptability and precision of additive manufacturing processes [6].

3. Technologies in additive construction

Additive manufacturing (AM) in construction introduces innovative processes that build structures layer-by-layer from digital designs. These processes improve material efficiency, enhance design flexibility, and reduce waste. The key AM processes applied in construction are extrusion-based 3D printing, selective binding, and shotcrete 3D printing (SC3DP).

3.1. Extrusion-based AM

Extrusion-based AM is the most widely used method in construction. This process involves extruding a concrete mixture through a nozzle, layering it to form walls, foundations, or entire buildings. The material used is specially formulated for smooth flow and quick setting. This method allows for large-scale construction with minimal material waste, making it ideal for projects ranging from residential housing to infrastructure. Its scalability and the ability to print on-site significantly reduce construction time and transportation costs [7].

3.2. Binder jetting

Binder jetting applies a binding agent to a powder bed, solidifying layers of material such as sand or concrete [8] (**Figure 1**). This process is particularly useful for producing intricate architectural elements, lightweight components, and structures with internal voids. For example, sand-based binder jetting has been used to create complex façade elements, reducing material consumption while maintaining structural integrity [9].

3.3. Shotcrete 3D printing (SC3DP)

The shotcrete 3D printing process (SC3DP) uses a fully automated robot arm to spray concrete layers using compressed air. The kinetic energy of the sprayed material ensures compaction and a strong mechanical bond between layers, improving bulk density and reducing porosity. SC3DP does not require formwork and is ideal for large-scale, load-bearing structures [9].

3.4. Proven 3D printing types in the construction industry

As the demand for 3D printers is constantly increasing in terms of the complexity and size of the components, various systems have been developed to cover this large area in the construction industry. The most popular 3D printers are presented below:

3.4.1. Gantry system

The gantry system is a type of robot used for printing prefabricated components. Its distinguishing feature is its X-, Y-, and Z-axis

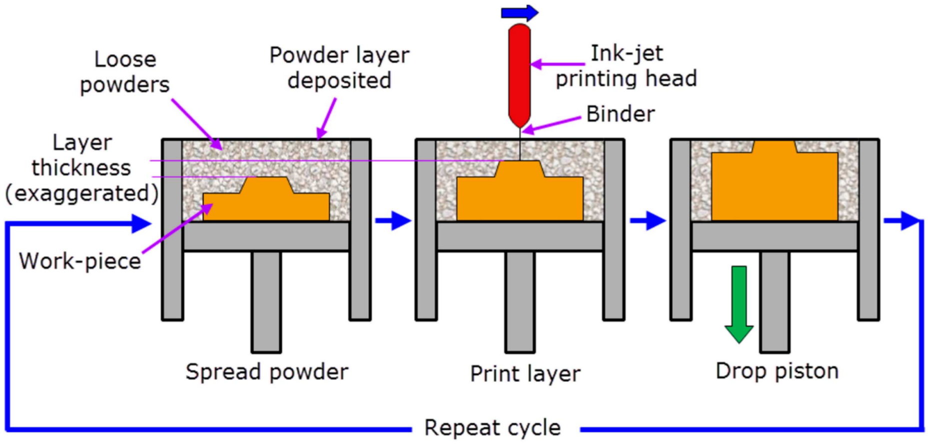

Figure 1 • Illustration of binder jet 3D printing technology. Reproduced from [8].

frame, allowing the robot to move freely in all directions. This frame also defines the boundaries of the build platform both horizontally and vertically. Concrete mix is delivered from an external silo through a pump and hose to the print head, where the object is built layer-by-layer using the moving nozzle. While the gantry robot can accommodate a width of up to 12 m and a height of 8 m, it can be extended along the Y-axis as needed. The system's maximum printing speed is one meter per second, though the practical speed is reduced to 0.25 m per second to allow for parallel manual tasks. Typically, a specially formulated concrete filament for additive manufacturing is used [10].

3.4.2. CONPrint3D printing technology

By comparison, the CONPrint3D system is designed to create formwork-free components without the need for a gantry frame. This system uses a truck-mounted concrete pump positioned outside the construction platform, which moves as needed based on the component size. CONPrint3D also includes a placing boom and a robot arm equipped with a print head, controlled by a predesigned BIM (Building Information Modeling) plan. Research suggests that the system can produce components over two meters long and up to three meters high. The material used is in situ concrete with an added accelerator to speed up the curing process [11].

The following section compares the use of robotic arm printing and gantry systems in construction, focusing on their effectiveness in large-scale projects. Recent studies highlight that robotic arm printing is particularly well suited for creating complex geometric shapes and large components due to its precision and adaptability. A major benefit is the ability to print directly on-site, reducing logistical costs and shortening construction times [11].

Gantry systems, also known as portal systems, excel in large-scale 3D printing and are ideal for building entire structures such as walls and foundations. Their scalability and automation offer high productivity, making them a cost-effective solution for constructing residential buildings and infrastructure [12].

4. Requirements for additive manufacturing materials

A key factor influencing the success of additive manufacturing is inevitably the choice of materials. As a rule, materials such as gravel, sand, and crushed stone are combined with binders such as polymers, fly ash, and Portland cement in order to achieve the desired properties.

4.1. Requirements for fresh concrete

The rheological properties of fresh concrete used in AM are critical for ensuring smooth and precise layer placement. The key requirements include:

-Pumpability: The concrete must flow evenly through the print head without clogging or interruptions [7].

-Extrudability: An undisturbed material flow through the print head is crucial to ensure a homogeneous distribution of fresh concrete. Attention must also be paid to the specified material output (material volume per time unit). In addition, the material must have a plastic consistency upon exiting the nozzle to ensure uniform layers. The nozzle configuration plays an important role here, as if the nozzle is set too high or too low, the layer thickness becomes too thin or too wide, which leads to a significant change in the component [7].

-Buildability: Early load-bearing capacity is required to prevent deformation under the weight of subsequent layers [13].

-Layer bonding: Fresh layers must bond effectively to ensure structural integrity [7]. To achieve a good layer bond, the layers must be installed freshly. **Figure 2** shows the layer bond after (a) 15 min, (b) 30 min, and (c) 60 min. A good bond can be seen after 15 min. After 30 min, only the surfaces exposed to air are bonded, but not the interior of the layers. If the layers are only applied after 60 min, it can be seen that each layer lies separately on top of the other and there is no bond. If it is necessary to continue printing the next day, epoxy resins, for example, can be applied to the already cured layer so that printing can continue.

The contradictory requirements of the four core requirements mentioned above must be precisely harmonized here. This is because a soft consistency is recommended for good pumpability of the concrete, while concrete with a plastic consistency is usually used for extrusion, and these concretes are difficult or impossible to pump. In addition, a softer consistency would lead to a loss of dimensional stability. A stiff, earth-moist concrete would be the best choice for installation, but this can neither be pumped nor extruded. The solution is a liquid concrete with good pumping properties, which becomes an extrudable, buildable concrete by adding a solidification accelerator in the print head [13].

4.2. Requirements for hardened concrete

The requirements for hardened concrete in AM are the same as those for conventional concrete production:

-Corrosion protection: The hardened concrete must protect reinforcement bars through the formation of calcium hydroxide.

-Water resistance: Structures must withstand environmental moisture and weather conditions.

-Compressive strength: Sufficient compressive strength is needed to support structural loads.

-Heat resistance: Hardened concrete must provide fire resistance to enhance safety [14].

5. Technological innovations and future trends

In recent years, technological advances in 3D printing have had a major impact on the construction industry. Breakthrough innovations, such as multi-material printing, enable the simultaneous use of different materials in a construction process. These developments have the potential to revolutionize construction practice by improving structural integrity, design flexibility, and material efficiency [15].

Multi-material printing is an advanced additive manufacturing technology in which multiple materials are used simultaneously in a single printing process. This technology enables the combination of different physical and chemical material properties in a single component, resulting in improved functionality and performance. In construction, this means that different building materials such as concrete, metal, plastics, and other specialized materials can be integrated into a single 3D printing process [16].

The use of multi-material printing in the construction industry offers numerous advantages. One of the most important is the ability to optimize the structural and functional properties of buildings. For example, load-bearing structures made of high-strength concrete and insulation layers made of special insulating materials can be produced in a single printing process. This improves energy efficiency and reduces material consumption and waste [15].

Another advantage of multi-material printing is the increased design flexibility. Architects and engineers can design more complex geometries and innovative structural shapes that would be difficult or impossible to realize using conventional construction methods. This enables not only aesthetically pleasing but also functionally optimized constructions [17].

Technological development in the field of multi-material printing is progressing rapidly. One of the most remarkable innovations is the ability to seamlessly integrate different materials and design the transitions between the materials in such a way that the mechanical and thermal properties of the structures are optimized. For example, a wall of load-bearing concrete and insulating foam can be produced in a single printing process, with the material transitions precisely controlled to avoid cracks and weak points [18].

The future of the construction industry will be characterized by the ongoing development of additive manufacturing (AM). AM technology has the potential to change engineering by enabling completely new solutions with newly combined materials. Funded by the German Research Foundation (DFG), the multi-material AM Research Centre at HTWK Leipzig focuses on the development of new large-scale systems that enable the integration of different materials and properties in one component. This can help to revolutionize the construction industry by integrating complex structures and functions into a single component, leading to improved functionality and performance [19].

Additive manufacturing (AM) is increasingly revolutionizing the construction industry. A key aspect of this change is the integration of Building Information Modeling (BIM). With BIM, digital twins of construction projects can be created, enabling the precise coordination of all design elements, including structural, electrical, and plumbing. This significantly increases efficiency and accuracy. For example, ICON uses BIM to optimize the pressure path and structure of wall systems in its construction projects. This enables comprehensive control and adjustment in real time, making construction processes more flexible and robust [20].

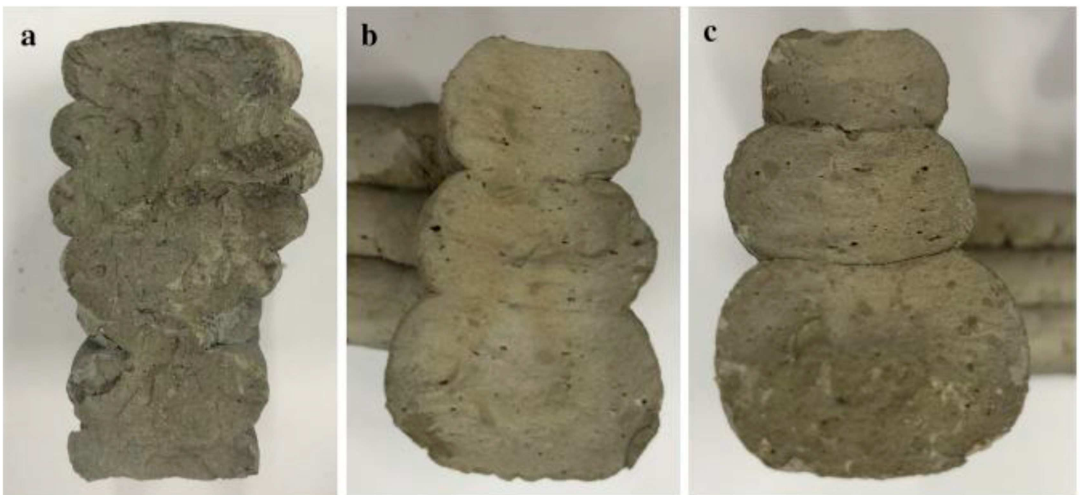

Figure 2 • Layer composite after (**a**) 15 min; (**b**) 30 min; (**c**) 60 min. Reproduced from [7].

The development of suitable materials is an essential prerequisite for the application of additive manufacturing technologies in the construction industry. At present, the choice of materials suitable for 3D printing is limited, which restricts the range of applications. However, advances such as carbon-reinforced polymers and fire-retardant composites open up promising prospects for expanding the range of applications. The new materials have mechanical properties close to those of metals and enable the realization of complex architectural structures that would be difficult to achieve using traditional methods [19].

In the construction industry, these innovative materials make it possible to optimize the strength and durability of printed structures and increase building safety. Advances such as the development of improved rheological properties and the creation of comprehensive material databases are helping to increase the consistency and repeatability of 3D printing processes. The aforementioned developments are crucial to increasing the versatility and efficiency of additive manufacturing and advancing its application in large-scale construction projects and infrastructure [21].

Another significant trend is increasing automation and the use of robotics. Robots are able to print complex structures precisely and efficiently, which shortens construction time and reduces costs. It is predicted that advanced robotic systems and automated processes will be increasingly used in construction projects in the future to increase productivity and reduce reliance on human labor. This development will enable complex construction projects to be completed faster and more cost-effectively [21].

The ability to quickly and cost-effectively print sustainable and robust structures makes additive manufacturing an attractive option for building homes, social facilities, and infrastructure in remote or extreme environments. This opens up new perspectives for tackling global challenges such as the housing shortage and supplies in disaster areas [20].

Although these promising developments give cause for optimism, there are still considerable challenges to overcome. Material limitations, printing speeds, and the consistency of material properties remain the biggest obstacles. Continuous research and development are therefore essential to overcome these problems. Of particular importance is the creation of comprehensive material databases and the improvement in software solutions for 3D printing planning. The creation of a robust database and the further development of printing technologies can contribute to a significant increase in the reliability and repeatability of additive manufacturing [21].

6. Environmental and sustainability implications

Sustainability in the construction industry is a highly relevant topic, given the significant environmental impact of construction and property sectors. Sustainable construction aims to reduce this impact while promoting long-term economic development. The concept of “sustainable construction” not only applies to the building process itself but also encompasses the planning stages. It involves taking a holistic approach to buildings by analyzing each individual building product. The primary goal is to encourage the mindful use of resources, conserve energy, and protect the environment [22].

Three-dimensional printing introduces new possibilities in architecture, offering sustainable solutions in building design. While the full environmental impact of 3D printing in construction has yet to be thoroughly analyzed, it shows promise in several areas:

- Resource efficiency: Three-dimensional printing can be more resource-efficient than traditional construction methods since it eliminates the need for molds or tools. This reduces both resource usage and costs, particularly by minimizing material waste; only the necessary amount of material is used for each component. This is a key factor in the resource efficiency of 3D printing. Additionally, additive manufacturing allows for the creation of complex components that are difficult or impossible to achieve through conventional methods, further reducing material usage and component weight, thus enhancing overall resource efficiency [23].
- Energy efficiency: The material efficiency achieved through 3D printing also leads to lower energy consumption. Three-dimensional-printed buildings often feature thick insulation and can be connected to efficient heating networks, resulting in greater energy efficiency compared to traditionally built structures. The ability to produce building components with lower density or built-in cavities improves thermal insulation, leading to lower energy costs [24].

A recent study explored the use of a new material, ACM (Advanced Composite Material), in 3D printing, as well as in heating and cooling systems. ACM offers greater sustainability compared to conventional materials and has a positive impact on energy efficiency. Heating and cooling systems are major energy consumers, so using an energy-efficient material like ACM is particularly valuable. This study found that ACM has higher thermal conductivity than conventional materials, improving heat transfer in these systems and lowering energy costs. However, these findings are preliminary and require further research to confirm the material’s effectiveness in real-world applications. Overall, 3D printing in construction holds significant potential for increasing energy efficiency and reducing resource consumption [25].

- Alternative material—geopolymer concrete

Geopolymer concrete offers a sustainable alternative to traditional Portland cement concrete, primarily due to the difference in binders. While Portland cement relies on limestone, geopolymer concrete is made by combining silicon and aluminum oxides from low-calcium fly ash with an alkaline liquid. The resulting paste binds coarse and fine aggregates, along with other unreacted materials. Like Portland cement, aggregates make up 75 to 80% of the total mass [26].

Portland cement production is highly resource-intensive and generates significant CO_2 emissions per ton of cement. In contrast, geopolymer concrete uses fly ash, a byproduct of energy production that would otherwise be sent to landfills. This reduces the demand for natural resources and significantly lowers CO_2 emissions. Another major advantage of geopolymer concrete is its improved fire resistance; because it does not retain water, it prevents spalling, thus providing better protection for reinforcements during fires. Additionally, geopolymer concrete has high compressive strength, making it particularly useful in road construction and 3D printing. Its early strength allows for quicker project completion and enhances stability when producing complex 3D-printed structures.

Despite the numerous advantages, there are challenges to the widespread adoption of geopolymer concrete. Currently, it has not been incorporated into standards like the cement standard DIN EN 197-1, which may create legal obstacles to its broader use [26].

7. Case studies and real-world implementations

7.1. Office of the future—Dubai

The Office of the Future in Dubai is a groundbreaking project demonstrating large-scale AM in commercial construction. Built in 2016, the office structure was created using an extrusion-based method, reducing material waste by 60% compared to traditional techniques. This project highlights the potential for AM to optimize both cost and environmental sustainability [27].

The Office of the Future is one of the first fully printed office buildings in the world and was opened in Dubai in 2016 (**Figure 3**). It was printed by the Chinese 3D printing company Winsun Global in China and shipped in individual segments to Dubai, where it was assembled by the Dubai Future Foundation [28]. The office building covers an area of 250 square meters and includes office and meeting rooms for up to 16 people. The construction project took just 17 days to print the main components and two days to install them on-site. The costs totaled USD 140,000 [29].

The design of the building is based on the principle of 'form follows function', which means that the design of the building was adapted to its function [31]. The segments were produced using a 3D printer called 'The Dragon' in a printing process based on extrusion with the following characteristics. The printer is 6 m high, 10 m wide, and 40 m long. A freely movable robot head, which is connected to a computer, prints the concrete by extrusion and thus produces the individual layers additively. The width of the individual layers produced is 50 mm with a thickness of 20 mm. The printing speed of the printer is up to 10 m per minute.

According to Winsun, the publication of photos of the 'Dragon' 3D printer is not permitted for reasons of confidentiality. However, a simplified representation of the printer setup is provided in **Figure 4** [28].

The 'Office of the Future' illustrates the application of 3D printing in the construction industry and demonstrates the potential of this technology for the production of buildings.

7.2. MX3D bridge—Amsterdam

The MX3D Bridge in Amsterdam is an innovative example of metal 3D printing applied to construction. Using robotic arms and wire arc additive manufacturing, the 12 m long bridge showcases the feasibility of AM for complex, load-bearing structures [32].

The MX3D bridge is another remarkable example of the use of 3D printing technology in the construction sector. The bridge demonstrates the potential of this technology to produce complex structures with high precision and load-bearing capacity.

The MX3D bridge in Amsterdam (**Figure 5**) is an innovative structure that was produced entirely using a 3D printing process. The bridge has a length of 12 m and a width of 6.3 m. It was opened in November 2018 and has an estimated lifespan of 30 years. The bridge consists of a total of 4.5 tons of stainless steel, which was produced in a printing time of six months using a special 3D printer. The MX3D bridge was primarily developed as a demonstration project to show the potential of 3D printing technology in construction. However, it is fully functional and accessible to pedestrians. The bridge has a maximum load capacity of 19.5 tons and therefore meets the requirements of the Dutch construction standards [32].

The construction costs of the bridge totaled EUR 2.3 million, which is high compared to conventional construction methods. The high cost of the custom-built 3D printer and the stainless steel are significant factors [33].

The 3D printer used to manufacture the MX3D bridge is a robotic arm designed and built by MX3D and controlled by specialized software. The printer uses a unique welding technology called arc additive manufacturing. This process allows the printer to melt and deposit the stainless-steel material layer-by-layer, creating the structure of the bridge. The printer is capable of printing an area of 6 × 6 × 3 m and operates at a speed of 400 mm per second [34].

Figure 3 • Office of the Future, Dubai. Reproduced from [30].

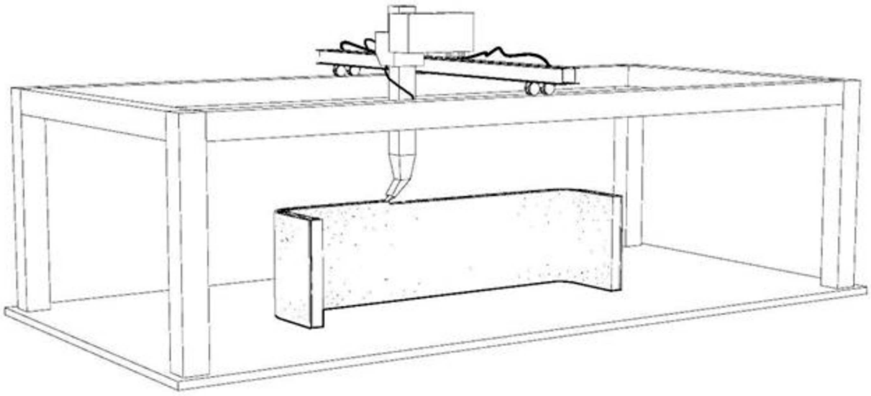

Figure 4 • Sketch of 'The Dragon' 3D printer from Winsun [28].

Figure 5 • MX3D Bridge, Amsterdam. Reproduced from [32].

7.3. YHNOVA project, Nantes, France

The YHNOVA project in Nantes, France, is an exemplary case of AM in residential construction. A 95-square-meter detached house was constructed using the robot-controlled BatiPrint3D system, which printed expanded polyurethane foam layers as a mold for concrete infill. This technique enabled fast and cost-effective construction, completing the printed structure in just 54 h [35].

7.4. ICON's 3D-printed homes, Mexico

ICON's 3D-printed homes in Mexico address affordable housing needs through the use of extrusion-based AM. These homes are cost-effective, sustainable, and demonstrate AM's potential for providing scalable housing solutions in developing countries [36, 37].

7.5. COBOD's infrastructure printing, India

COBOD's concrete printing technology has been used to construct infrastructure projects in India, such as footbridges and small-scale public facilities (**Figure 6**). These applications highlight AM's versatility and potential for creating durable and sustainable structures [38–40].

7.6. MODULA 3D—pioneering 3D construction in Indonesia

In Bakauheni, Lampung Province, Modula3D—a joint venture between Bakrie & Brothers (BNBR) and COBOD International—successfully constructed Indonesia's first 3D-printed house using BOD3 technology (**Figure 7**) [41]. The project includes a 530 m^2 community village for SEAPI employees, built with locally sourced concrete and prefabricated materials to reduce environmental impact. This case demonstrates the practical application of 3D construction printing in Indonesia and contributes to the growing evidence of its viability for sustainable and efficient housing development.

The YHNOVA project demonstrated several important benefits of additive manufacturing (AM) in residential construction. Automation significantly reduced labor requirements and minimized the risk of industrial accidents. In addition, the precise control over material usage reduced waste and improved resource efficiency. The use of polyurethane foam provided both structural function and thermal insulation, enhancing the building's energy performance. Architecturally, the project showcased how AM can enable complex geometric designs that would be difficult or costly to construct using conventional methods [42].

Similar advantages were evident across other case studies reviewed in this paper. The Office of the Future in Dubai demonstrated rapid construction using prefabricated AM segments. The MX3D Bridge in Amsterdam highlighted the structural potential of metal AM for complex, load-bearing designs. ICON's 3D-printed homes in Mexico offered scalable solutions for affordable housing, while COBOD's infrastructure projects in India illustrated the versatility of AM for public facilities. Notably, the MODULA 3D project in Indonesia successfully utilized locally sourced concrete and prefa-

Figure 6 • Printed post office in Bengaluru, India. Reproduced from [38].

Figure 7 • Three-dimensional-printed house constructed by Modula3D in Bakauheni, Lampung Province, Indonesia (image courtesy of Modula3D, permission granted).

bricated materials, showcasing the role of AM in promoting sustainability and contextual adaptation in developing regions. Collectively, these projects confirm that AM can accelerate construction timelines, reduce costs, expand design possibilities, and support sustainable building practices across diverse contexts. Furthermore, they underscore the need for close collaboration between architects, engineers, and AM specialists, along with the development of updated legal and regulatory frameworks to support the broader adoption of AM in construction [43].

8. Future prospects

The future of additive manufacturing (AM) in construction is poised to bring about transformative advancements, driven by emerging technologies and material innovations. Key areas of future focus include the following:

-Integration with artificial intelligence (AI): AI-powered systems can enhance AM by enabling real-time monitoring, defect detection, and dynamic adjustment of printing parameters. Furthermore, AI can optimize designs for material efficiency and load distribution. Generative design tools integrated with AM are helping create more efficient structures, while future research should focus on further optimizing processes, material selection, and real-time construction monitoring [44, 45].

-Carbon-neutral materials: Research into carbon-neutral and bio-based materials for AM, such as algae-based polymers or recycled construction waste, could further reduce environmental impact. These materials are aligned with global sustainability goals and offer significant potential for scalable use [46–48].

- Robotic and autonomous systems: Advanced robotics and autonomous systems could enhance the scalability of AM, allowing for the construction of larger, more complex structures with minimal human intervention. Robotic arms equipped with AI-guided motion systems are being tested to improve precision and efficiency [49, 50].

- Hybrid AM technologies: Combining AM with traditional methods may allow for greater design flexibility and integration into existing workflows, bridging gaps in scalability and cost-effectiveness [51, 52].

- Expanded applications: AM is expected to play a crucial role in disaster relief, creating modular housing and infrastructure in response to natural disasters. Additionally, AM's role in building space habitats and underwater structures is gaining attention, reflecting its adaptability for extreme environments [53, 54].

By addressing these emerging trends, the construction industry can further leverage AM to meet future challenges and opportunities.

9. Conclusions

Additive manufacturing (AM) represents a paradigm shift in construction engineering, offering a technically advanced, resource-efficient alternative to traditional building methods. This review has highlighted how AM technologies—such as extrusion-based printing, binder jetting, and shotcrete 3D printing—can deliver significant engineering benefits, including precision, scalability, and adaptability in complex structural applications. Case studies from France, Dubai, the Netherlands, Mexico, India, and Indonesia have demonstrated AM's capability to deliver not only innovative designs but also practical solutions in diverse construction settings.

From an engineering perspective, AM enables the optimization of structural forms, reduction in labor-intensive processes, and customization of materials and geometries. At the same time, its potential for reducing material waste, lowering carbon footprints, and incorporating sustainable alternatives such as geopolymer concrete aligns directly with the goals of sustainable development and climate-resilient infrastructure.

Nevertheless, challenges remain. The current limitations in material availability, lack of standardized testing protocols, and fragmented regulatory environments pose barriers to large-scale adoption. Overcoming these will require interdisciplinary collaboration, the development of robust material databases, and the integration of digital design tools with advanced automation and AI.

Moving forward, AM holds significant promise for addressing urgent global needs, such as affordable housing, low-impact infrastructure, and rapid construction in disaster-prone or remote areas. Its continued evolution will be a key driver in engineering more sustainable, resilient, and efficient built environments worldwide.

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Conflict of interest

The authors declare no conflicts of interest.

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