

Advantages and Benefits of Additive Manufacturing in the Construction Industry: A Systematic Review

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Abstract. Additive manufacturing (AM) has become a technology emerging in the construction industry, after revolutionizing other industry sectors. To define its benefits, we conducted a systematic review investigating the advantages of AM in construction based on a thorough screening of 30 papers retrieved from Scopus and Web of Science (WoS) databases. A PRISMA approach was adhered to ensure transparency and rigor in paper selection. The study identifies 11 main categories of benefits that were reviewed to determine the prevalence and relevance of each benefit across the studies. The results stress that AM can lead to revolutionary efficiency improvements, material efficiency, and design flexibility, but material durability concerns, widespread use, and the integration of emerging technologies are a few challenges. The paper concludes that although AM offers promising prospects for the construction industry, additional research needs to be carried out to overcome its drawbacks and explore its full potential.

Keywords: Additive manufacturing, benefits, PRISMA, Efficiency, design flexibility

1 Introduction

The construction industry is a domain that has known a slow evolution in the last decades, since this domain is characterized by a one-of-a-kind project, high time, and energy consumption.

But nowadays, this industry is undergoing a significant transformation after the integration of digitalization and robotics, especially additive manufacturing (AM). A technology that allows layer-by-layer structure fabrication by transforming numerical data from CAD to physical objects.

The integration of this technology has become necessary to provide more efficient, accurate, and innovative construction methods than traditional labor-intensive approaches [1].

AM is also known as 3D printing; it encompasses a number of techniques that enable the direct deposition, bonding, or fusion of materials, opening up new possibilities in architectural design and structural engineering [2].

One of the AM technologies emerging as potential solutions in modern construction is Concrete extrusion, or 3D concrete printing (3DCP), which is one of the most widespread techniques, in which cement-based material is deposited in layers to fabricate structural components [3]. Another different approach to additive manufacturing is powder bed fusion, which uses high-power lasers or electron beams to selectively melt powdered materials, enabling the printing of complex, highly detailed architectural elements [4]. There's also Binder Jet, which is also increasingly used, based on the application of a liquid binder to a powder bed to create solid layers, proving optimal for customized, lightweight building elements [2]. In addition, there's contour fabrication, a large-scale AM method using robotic systems to deposit layers of material, enabling buildings to be constructed rapidly with minimal human labor [5].

In the past few years, 3D printing technology has been applied in the construction sector, resulting in revolutionary projects all over the world. These projects highlight innovation, efficiency, and sustainability.

For example, in 2018 in Italy, Gaia House (Figure 1) built a 12 m² ecological house using natural materials harvested from its site [6]. Canal House, an Italian initiative begun in 2016, also included a 13-room building made available to the public that showcased advancements in 3D-printed material and building [7].

Similarly, in 2016, Shamballa Village built large, sustainable houses made of mud or clay with reinforced plant fibers [8].

There is also the Office building in Dubai, UAE, with a size of 250 m², that was constructed in 2016 by the Chinese construction company, Winsun. The building was printed with a printer having an automated robotic arm for precise material deposition [9].

Also, we can find the Cyclist Bridge in the Netherlands, completed in 2017, a project that showcased the durable potential of 3D-printed reinforced concrete with its 8-meter-long bridge that can carry two tons [10].

Worldwide, projects continue to show creative use of materials available locally as well as sustainable practices. In Russia, the Apis Cor project (Figure 2) produced a 38m² rotor-shaped home building in 2016 in an attempt to save on expenses [11]. Also, in the Philippines, a hotel was added onto 130m² in 2015 using sand and volcanic ash for more resilient, stickier walls [12].



Fig. 1. Gaia House



Fig. 2. Apis cor project

Many projects were applied in the construction field using different robots to enhance the efficiency of the construction domain and provide better quality in the minimum time. Therefore, the objective of this paper is to investigate the advantages of AM application in the construction industry.

2 Methodology

This systematic review is carried out per the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to ensure reproducibility and transparency. A comprehensive search via Scopus and Web of Science was conducted to find relevant studies on how additive manufacturing will positively impact the construction industry. The following formula was inserted into the search bar to eliminate the possibility of too many papers being included and make the process systematic and focused:

("additive manufacturing" OR "3D printing") AND ("construction industry" OR "building industry") AND ("advantages" OR "benefits") AND ("implementation" OR "adoption").

To get the pertinent articles, we have first applied filters as exclusion/inclusion criteria, so we have kept the studies focusing on the benefits of AM in the subject areas: Engineering, Environmental Science, Energy, Materials Science, Construction Building Technology, Civil Engineering, Architecture written in English, and we excluded the others.

Studies that were exported were first screened for duplicates between the two databases and later screened based on titles and abstracts. Further screening of relevance was done with full-text articles, and the final analysis was carried out only with articles that survived predefined inclusion criteria, which are the subject area and the pertinence of the article's content.

3 RESULTS

A total of 81 articles were collected from Scopus and Web of Science. After removing 22 duplicates, 59 articles remained. Following a title and abstract screening, 6 articles were deemed irrelevant to our research topic. We then attempted to access the full texts and successfully retrieved 33 articles. After a full-text analysis, 3 articles were excluded as they did not contain the necessary information for our research (as shown in the PRISMA Diagram [13]).

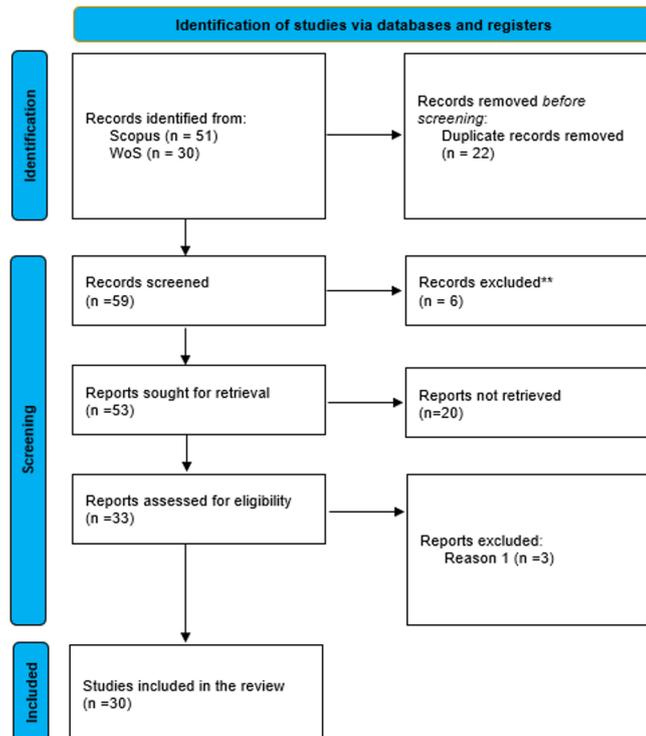


Fig. 3. PRISMA Diagram

Of the 30 articles left, we had different types of documents, 40% were from conference papers, 33% were from journal articles, 20% from reviews, and 7% from book chapters (Figure 4), these articles were from 18 countries, but the top six are: Germany with 5 articles, Australia, Russia, New Zealand with 3 articles each, then come India and USA with 2 articles each (Figure 5).

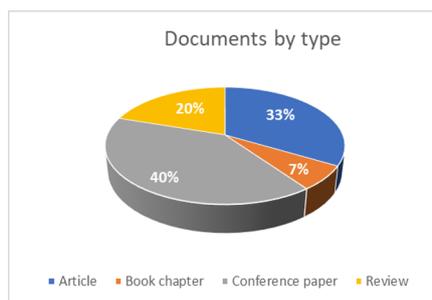


Fig. 4. Documents by type

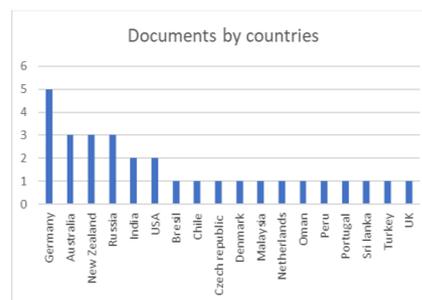


Fig. 5. Documents by country

The analysis of the articles identifies too many advantages of implementing AM in the construction industry. We regrouped them into 11 categories, which are: Efficiency, Design Flexibility, Sustainability, Material Efficiency, Cost Efficiency, Customization, Speed, Design Quality, Safety, Innovation/Technology Integration, and Social Impact.

The frequency of each category varies across the articles, as shown in the following table:

Advantage Id	Advantage Category	Appearance N°	Articles
ADV1	Efficiency	29	[14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [37], [38], [39], [40], [41], [42], [43]
ADV2	Design Flexibility	26	[14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [33], [34], [35], [37], [38], [40], [41], [42]
ADV3	Sustainability	23	[14], [15], [16], [17], [18], [19], [20], [21], [23], [25], [26], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [40], [41]
ADV4	Material Efficiency	22	[15] [16] [17] [18] [20] [22] [23] [24] [26] [27] [28] [29] [30] [31] [32] [33] [35] [37] [38] [40] [41] [43]
ADV5	Cost Efficiency	20	[14], [19], [21], [22], [23], [25], [27], [28], [29], [31], [32], [33], [34], [35], [37], [38], [39], [40], [41], [42]
ADV6	Customization	15	[14] [43] [16] [41] [40] [19] [35] [21] [22] [33] [24] [32] [30] [27] [29]
ADV7	Speed	14	[14] [43] [41] [17] [18] [40] [38] [21] [22] [36] [35] [33] [30] [28]
ADV8	Design Quality	12	[15] [16] [17] [21] [24] [29] [34] [36] [37] [38] [39] [43]
ADV9	Safety	11	[14] [43] [41] [40] [18] [39] [35] [34] [32] [28] [27]
ADV10	Innovation/Technology Integration	8	[14] [38] [36] [17] [24] [23] [22] [21]
ADV11	Social Impact	3	[34], [39],[42]

Table 1. Advantages categories.

4 Discussion

Following the articles from [14] to [43], additive manufacturing has several advantages if applied in the construction industry; each article zoomed in on some of them, and this is the summary of the key points we found:

1. Efficiency is the most commonly mentioned advantage in 29 articles, explaining how AM enables waste minimization, resource optimization, and process enhancement. This advantage focuses on optimizing overall production and work efficiency

in construction through cost-saving, reducing timelines, and minimizing labor through automation, precise material usage, and computer-aided techniques like VR (Virtual Reality) and BIM (Building Information Modeling).

2. Design Flexibility, referred to 26 times, presents AM's capability to design complex, customized, and diverse structures. It enables architects and engineers to overcome traditional limitations through 3D modeling, generative design, and rapid prototyping, allowing for creative, customized, and sustainable buildings.
3. Sustainability is the environmental benefit of using AM in the construction process, in term of reducing environmental impact by minimizing waste generation, recycling material, conserving energy, and reducing emissions, which is advantageous in the production of cleaner, climate-resilient buildings. It was cited in 23 papers.
4. Material Efficiency, mentioned 23 times, means the way in which AM reduces the wastage of material and optimizes the utilization of resources. It improves the properties of the material, eliminates waste, and delivers the optimum materials in optimum quantities.
5. Cost Efficiency involves minimizing the cost of building through optimum resources, processes, and time by the use of AM, it involves cost savings on labor, operations, and material. It was mentioned in 20 articles.
6. Customization portrays AM's ability to customize designs and products for specific needs, either for a single buyer or local requirements, providing tailored and personalized construction solutions. It was noted in 15 articles.
7. AM can also speed up the building activity by enhancing planning, productivity, and ensuring faster production, assembly, and delivery. This advantage was highlighted in 14 articles.
8. Design quality, cited 12 times, refers to the ability of additive manufacturing to produce high-quality structures that offer optimal strength and performance through durability, structural integrity, and optimal mechanical properties.
9. Safety highlights how AM reduces risks, improves the safety of labor, and makes building sites safer by minimizing human exposure to hazards. This advantage was cited in 11 articles.
10. Innovation and Technology Integration refers to how AM integrates new technologies like automation, digital workflows, and smart systems into the construction process, enhancing the process as a whole. It was discussed in 8 articles.
11. Social Impact refers to the broader positive contribution to society from AM in construction, such as enhanced living standards, jobs, and positive effects on the community. Sited only in 3 articles, it shows that AM could make a difference beyond pure technical or financial returns.

After carefully reading the articles and detailing the benefits step by step, we discovered that they fell into more general and overarching categories:

- Technical benefits, which include aspects directly related to engineering, performance, and technological capabilities. These include design flexibility, customization, design quality, and the integration of innovation and technology.
- Economic benefits, including cost savings, increased productivity, and better resource utilization, such as efficiency, profitability, and speed.

- Environmental benefits, aimed at reducing the ecological footprint and promoting sustainable resource consumption. This category includes sustainability and material efficiency.
- Social benefits, which focus on human well-being, safety, and the overall impact on society. These are safety and social impact.

While additive manufacturing in construction has many advantages according to previous research, it is still limited in developed countries. As the diagram of documents by country reveals, the majority of experiments aimed at truly measuring the difference between traditional and additive construction require the use of advanced technologies to compare performance with and without additive manufacturing.

However, this has not prevented construction companies from highlighting in their project presentations that the benefits of cost reduction are particularly visible for those involved in mass production, where the gains can be truly valorized, like in the Apis cor company [44].

Additive manufacturing enables the creation of complex geometries with increased precision while minimizing resource consumption. However, the main constraint remains the strength and durability of the materials used, an essential point to discuss to ensure the long-term strength of the structures.

It is also noted that only three articles have addressed the social impact of additive manufacturing. This impact includes the mass production of affordable social housing, helping to address the housing shortage, as well as the creation of new job opportunities, since automation requires new skills and specific knowledge. In addition, the use of BIM [39] improves communication between stakeholders.

While this review is a comprehensive analysis, it is limited to Scopus and Web of Science-indexed literature, which could potentially overlook significant research published in other databases.

Moreover, the categorization of benefits was carried out using thematic analysis, which, despite the attempt at objectivity, could be susceptible to interpretation.

Future researches need to investigate further the social aspects of additive manufacturing in construction since it was under-represented in these previous studies. Additionally, additional empirical research is required to quantify cost savings and efficiency gains reported in the literature.

5 Conclusion & Perspectives

This paper highlights various strengths of additive manufacturing in construction, like cost-effectiveness, efficiency, saving or elimination of material wastage, flexibility of design, and increased safety. All these positives make the AM capable of revamping the traditional construction process. Quoted strengths listed across studies vary, with some specifying advantages in financial terms and others in environmental as well as technical terms.

Despite the promise, building the AM faces a series of challenges. The strength and sustainability of printed items remain an issue, which requires further research and standardization. Secondly, adoption of risk management is still low across much of the

globe, particularly developing countries, due to high start-up costs, regulatory issues, and the need for specialist knowledge. Another important omission in the literature is that little is said about the social impact of AD, namely its role in alleviating housing shortages and labor force transformation. Future research will need to focus on large-scale deployment, long-term durability of the materials, and how computer-aided manufacturing is combined with future technologies such as AI and robotics. Along with this, interdisciplinarity to facilitate interaction among engineers, architects, policymakers, and material scientists will need to be obtained to realize the actual potential of AM in construction. In conclusion, even though AM holds the potential to revolutionize the construction industry, its widespread application is contingent upon the removal of physical, economic and regulatory barriers. Through ongoing innovation and study, AM can rethink the construction industry as a more efficient, sustainable and responsive industry capable of adapting to future requirements.

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