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CHAPTER 7

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Abstract Additive manufacturing (AM), including 3D printing, has the potential to transform the construction industry. AM allows the construction industry to use complex and innovative geometries to build an object, building block, wall, or frame from a computer model. As such, it has potential opportunities for the construction industry and specific applications in the deep renovation process. While AM can provide significant benefits in the deep renovation process, it is not without its own environmental footprint and barriers. In this chapter, AM is defined, and the main materials used within the construction industry are outlined. This chapter

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also explores the benefits and challenges of implementing AM within the construction industry before concluding with a discussion of the future areas of development for AM in construction.

Keywords Additive manufacturing • 3D printing technology • Construction industry • 3D concrete printing

7.1 Introduction

Additive manufacturing (AM) is the process of fabricating three-dimensional (3D) physical objects by connecting materials together in a layer-based manner following a specific computer design (Guo & Leu, 2013). The concept of AM was first introduced by Chuck Hull (1984), who used ultraviolet (UV) light to harden a layer of a liquid polymer (Wong & Hernandez, 2012). In recent years, AM has evolved to include a wide range of solutions and techniques, including selective laser sintering (SLS), direct metal laser sintering (DMLS), laser engineered net shaping (LENS), electron beam melting (EBM), fused deposition modelling (FDM), and digital light processing (DLP) (Albar et al., 2020). These methods enable the use of different materials in AM such as metals, composites, ceramics, and polymers and the production of end-parts that are capable of serving different purposes (Albar et al., 2020). The rapid development of AM has encouraged researchers and practitioners to adopt this technology in the construction sector as a cost-effective solution to create various structural components, regardless of their complexity, with minimum waste (Lyu et al., 2021).

In the construction sector, a significant focus of research and development was observed towards the development of different AM methods to cope with the unique characteristics of cementitious materials. These mostly include material extrusion and particle-bed processes as well as other generative approaches such as Smart Dynamic Casting (Paolini et al., 2019). Aggregate-based materials such as concrete are most commonly used in AM for the construction industry (Paolini et al., 2019). According to recent estimates, the value of the AM market for concrete printing was over $310 million in 2019 and is expected to reach $40 billion by 2027 with an annual growth rate of 116% (Pawar & Rohit Sawant, 2020). These figures suggest that AM will be rapidly and globally adopted by the construction sector, driven by the promise of reduced environmental impact, support for more complex designs, and more cost-effective construction (Mart et al., 2022). It is important to note that while AM processes are less labour-intensive, the adoption of AM in construction is expected to result in significant job creation, including new high-value roles, for example, 3D printer manufacturing and maintenance engineers, mixture designers, materials suppliers, and specialist software developers (Avrutis et al., 2019).

The remainder of this chapter introduces and defines AM and provides an overview of the main benefits of AM as well as its main applications in construction and deep renovation[1] projects. Finally, practical challenges in the implementation of additive manufacturing are summarised, and upcoming advancements are briefly discussed in the final section.

7.2 Additive Manufacturing in Construction and Deep Renovation

Significant advancements have been made in concrete 3D printing in recent years thanks to the introduction of a variety of different materials in producing concrete mixtures. Ordinary Portland cement (OPC) was the first material adopted by AM to produce full-scale printed concrete structures (Chougan et al., 2021). There are, however, concerns regarding the impact of OPC on the environment, which remains an issue with its implementation in AM. Cement production accounts for 5–7% of the total world CO_2 emissions (Chougan et al., 2021). In order to achieve a sustainable built environment and reduce CO_2 emissions, many researchers have suggested the implementation of alkali-activated materials (AAMs) as they can entirely replace OPC and produce a low-carbon binder (Chougan et al., 2021). In this case, materials such as metakaolin are used as aluminosilicate cementitious binders along with activators such as potassium silicate, sodium metasilicate, and potassium hydroxide to obtain AAM binders capable of building successful 3D printed structures (Alghamdi et al., 2019). Others have suggested enhancing AAMs' rheological properties by integrating modifying agents and additives in the mixtures like polypropylene (PP), polyvinyl alcohol (PVA), nano-graphite (NG), halloysite clay minerals, and attapulgite to improve the buildability, printability, and mechanical performance of AAMs for 3D printing (Chougan et al., 2021; Chougan et al., 2022).

The application of AM is not limited to the 3D printing of cementitious composites. Aside from cementitious composites, other categories of materials, such as polymers and metals, have also been used, particularly in renovation works. With the continuous development of AM technology,

[1] Chapter 1 in this book provides a detailed definition of deep renovation.

the customisation of parts and components needed for particular purposes in renovation projects became possible. For instance, the production and installation of precast concrete façade sections can be particularly challenging due to their complexity and the wide variation in their configurations in different buildings. In this context, AM could enhance the quality of the produced façade sections due to its higher degree of flexibility compared to standard production methods while also minimising post-installation problems such as air and water leakages. AM can also be used to print moulds that have the ability to produce façade sections with efficient passive shading (Harris, 2022).

AM is being scaled increasingly. Big area additive manufacturing (BAAM), a 3D-printing process similar to FDM, has been developed to construct segments of cylindrical single-floored building components out of polymer materials such as neat ABS and CF-ABS (Biswas et al., 2017). In addition, robotic 3D metal printing, also known as wire arc additive manufacturing (WAAM), can be used to fabricate highly tailored and engineered steel connectors for large structures in the construction sector (Xin et al., 2021).

More examples of the cementitious composites, polymer, and metal additive manufacturing technologies in building structures can be found in Table 7.1.

7.3 Benefits of Additive Manufacturing in Construction

Historically, the construction industry was characterised by high energy consumption (i.e., 40% of the global energy consumption), high solid waste production (i.e., 40% of the global waste production), high greenhouse gases emission (i.e., 38% of the global CO_2 emission), and high water depletion (i.e., 12% of the global water depletion) (Comstock et al., 2012). It has an undeniably high environmental footprint. Growing public interest in sustainability highlights the necessity for novel construction techniques and materials to mitigate traditional construction's high environmental impacts. AM technology represents one possible way for construction companies to use available resources more efficiently. In fact, one of the main advantages of AM is the minimisation of raw materials consumption, which reduces the level of waste generated during construction (Yao et al., 2020; Valente et al., 2022).

A second related advantage of AM compared to traditional construction methods is the capacity to produce complicated large-scale structures

Table 7.1 Various materials and technologies used in additive manufacturing

Material category	*Technology*	*AM process*	*Reference*
Cementitious composites	OPC-based 3D printing	Extrusion-based	Cuevas et al. (2021)
	AAM 3D printing	Extrusion-based	Chougan et al. (2020)
Polymers	Qingdao Unique Products Develop	Extrusion-based	Feng and Yuhong (2014)
	BAAM	Extrusion-based	Love (2015)
	C-Fab	Extrusion-based	Technology (2017)
	Digital Construction Platform (DCP)	Extrusion-based	Keating et al. (2014)
	FreeFAB™ Wax	Extrusion-based	Gardiner et al. (2016)
Metals	Maraging steel	Powder bed fusion	Galjaard et al. (2015)
	Multiple	Powder bed fusion	Mrazovic (2016)
	Stainless steel	Direct energy deposition	Joosten (2015)
	Aluminium	Powder bed fusion	Strauss and Knaack (2015)

while also minimising raw materials waste by lowering or eliminating the necessity of conventional formworks (Wangler et al., 2016). The increasing use of cementitious materials (e.g., concrete) in construction, along with the high costs of formwork production, emphasises the value of additive manufacturing technologies in constructing complex structures. Furthermore, the ability to fabricate complex objects enables building structures to possess "multi-functionality" by facilitating the integration of services, including piping, insulation, and electrical setups, and offering a secondary function through its complex geometry, such as instinct thermal insulation (De Schutter et al., 2018). This may be particularly beneficial in the context of deep renovation where the number of building elements to be replaced is quite large and existing building constraints make the installation of different individual elements quite challenging. As the structure becomes more complex, AM technology becomes more advantageous. In the same way, AM may be less cost-effective and less environmentally beneficial for more "standard" designs (Labonnote & Rüther, 2017).

Finally, as AM processes remove the need for conventional energy-consuming processes and labour-intensive activities like concrete pumping and casting, shuttering, material logistics, and steel fixing, it reduces the costs of on-site assembly and construction, minimises human error, and improves productivity (Avrutis et al., 2019).

7.4 Practical Challenges for AM in the Construction Industry

Despite the benefits of AM to the construction industry, there are a series of major challenges to its implementation, which could hinder adoption. Firstly, the high cost of obtaining 3D printing equipment, as well as printers' transportation and logistics, could arguably represent a significant obstacle to the widespread application of 3D printing technology in the construction industry. Despite the technological advantages, many construction companies are still unable to justify or afford an investment in 3D printing equipment.

Secondly, while AM technology reduces human errors and the need for workers on construction sites, finding qualified individuals to work with AM remains difficult (Deloitte, 2016). In addition, the shorter production and installation time comes at the cost of a longer design phase, which requires significantly higher effort and specialised modelling skills (Buswell et al., 2018). These labour supply problems are multifaceted. They are driven by a decline in the attractiveness of the manufacturing and construction sector, a lack of labour supply from the education sector with sufficient STEM skills and knowledge, a shortage of AM-specific training programmes, and a general lack of AM knowledge and culture in many construction and construction-related manufacturing companies (Deloitte, 2016). Where skilled labour does exist, firms may face significant upskilling, skills maintenance, and retention challenges until the AM skills and training gaps are addressed (Deloitte, 2016).

Thirdly, there is a general lack of regulation, standardisation, and testing of AM printing structures and materials. Standards in AM facilitate technology adoption, boost confidence in the quality and safety of AM processes, materials, and outputs, and support the competitiveness of AM and construction companies (Martínez-García et al., 2021). While standards have been developed by a wide range of organisations, for example, the German Society of Mechanical Engineers, the ISO, and the American

Society for Testing and Materials (ASTM), there would appear to be some challenges in aligning existing standards for testing the mechanical properties of more traditional materials and manufactured polymers and composites, and those generated through AM (Forster, 2015; Martínez-García et al., 2021). Indeed, it is fair to say that the flexibility AM introduces in terms of design and material use complicates testing and standards. Martínez-García et al. (2021) note that despite significant efforts by the ISO and ASTM, AM technology requires specific standards in all the stages of the product development, including design, materials, manufacturing, and final part.

Finally, and somewhat contradictory to the benefits presented in the previous section, the environmental impact of AM may not be entirely positive. AM is still at an early stage of development and use in the construction sector. Much AM use still involves the use of environmentally hazardous substances (e.g., cement) in considerable quantities as well as substantial equipment and non-eco-friendly manufacturing (Agustí-Juan & Habert, 2017; Agustí-Juan et al., 2017). AM units are often powered by lithium batteries and the electricity consumption throughout the fabrication process may offset the waste reduction and the other environmental benefits generated by AM (Agustí-Juan & Habert, 2017; Agustí-Juan et al., 2017).

7.5 Future Areas of Development

AM is particularly economically beneficial for large-scale building developments due to the enhanced geometrical freedom enabled by this technology. Compared to traditional construction methods, AM technology provides architecture designers the geometric freedom to create ideal complex structures while minimising the use of materials (Labonnote et al., 2016). However, while AM construction methods have been extensively adopted in real applications, there is still a lack of knowledge regarding large-scale AM. As a result, large-scale AM can be considered an escalated challenge compared to lab-scale 3D printing. Large-scale AM is typically more complicated than lab-scale 3D printing, as several practical construction challenges must be addressed. Large-scale AM involves a set of discrete technologies and thus requires consideration of a very different set of parameters, not least materials, reinforcing admixtures, economics, environmental optimisations, structural limitations, and 3D printing system design (Xiao et al., 2021). The majority of the existing studies concentrated on 3D printing of cementitious composites containing fine aggregate (i.e., mortar); however, cementitious composites with coarse aggregate (i.e., concrete) are attracting considerable interest because of their remarkable mechanical and cost-efficiency advantages (Xiao et al., 2021). Therefore, further investigation is required to determine the impact of using coarse aggregates to move towards cementitious concretes in order to fulfil the large-scale 3D printing requirements.

4D printing, a novel approach that includes a fourth dimension (i.e., time and smart behaviour), can allow 3D-printed items to transform their geometry and behaviour throughout time in response to specific conditions such as radiation, light, and temperature. The smart behaviour of 4D printing in shifting configurations for self-assembly, multi-functionality, and self-repair is a crucial breakthrough in AM technology. While 4D printing delivers all of the advantages of 3D printing, its use in the construction sector is in its infancy, posing obstacles such as a considerable need for improved computer analysis, new design concepts, structure validation, and standardisation (Pan & Zhang, 2021).

7.6 Conclusion

AM technology represents a valuable innovation in the construction sector and is gaining popularity. There are many benefits to AM, such as its potential to significantly reduce the consumption rate of raw materials, reduce the generated waste during construction, lower CO_2 emissions, reduce labour costs, minimise human errors, and improve productivity. Many complex designs, at a building or part-level, that previously were considered too problematic or costly for execution on-site can be easily implemented with the help of AM technology. Widespread adoption is not without challenges. In fact, some issues still exist in relation to process, materials, geometric complexity, software and building integration, and the standards associated with these elements. In order to capitalise on the impact of AM, additional research is needed to support the better integration of this technology in the construction sector. Moreover, to enable the rapid growth of this technology, standardised testing and quality control methods should be established to improve information sharing and benchmarking. Finally, without a pipeline of qualified labour, the full potential of AM will not be realised. This will be a key challenge to overcome if the technology is to be pushed further into full-scale industrialisation.

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