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REPORT

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Additive manufacturing in construction: A review on technologies, processes, materials, and their applications of 3D and 4D printing

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Abstract

In this paper, the current state of the art of additive manufacturing (AM) in the construction industry to manufacture on large scales is reviewed. The central concept of AM was defined, and it has been highlighted in the large use in several sectors. The main advantages that AM offers in the construction industry were described with at the same time the most important challenges that need to be addressed for real use. The main AM technologies solutions on large scales were described from more compact solutions like gantry technology to more flexible and free technology solutions. The choice of an AM solution rather than another is closely linked to the materials to be used and the building component to be built. Regarding materials, the research focused on materials based on aggregates, metals, and polymers. The application of AM in the construction field requires more studies and further research.

KEYWORDS

3D printing, additive construction, additive manufacturing, construction process, digitalization

1 | INTRODUCTION

Additive manufacturing (AM) is defined by ISO/ASTM 529000:2015 as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”.[1] Design, production and assembly processes should be digitally controlled at least to some extent. The main characteristics are then the use of an additive technology rather than subtractive one[2] and the possibility to produce complex shapes and geometries automatically through a 3D model without any tooling, mold and fixtures. As a consequence, it is possible to create entirely new production methods and business strategies.[3] AM has been used for years to build physical prototype and progressively to build end-use parts for various industries, such as biomedical, aerospace, automotive, microelectronics (MEMS), energy, consumer products up to reaching the construction sector.[3,4] In recent years there has been an increase in research on printing methods and developments that can be attributed to the several advantages and opportunities that AM offers; regarding the construction field we can cite the following:

- *Automation of the construction process:* AM allows for the fully automated fabrication of buildings or building components, both on-site and off-site.[3]
- *Freedom in geometries:* with AM, it is possible to create complex and customizable shapes and geometries that would be difficult and more expensive with traditional construction techniques.
  AM (and structural optimization procedures) makes it possible to easily realize lightweight structures (material minimization) whose geometry can be suitably designed to locally define its structural response.[5]
  The potential of modeling and simulation software combined with the accuracy and freedom in geometry guaranteed by AM leads to highly innovative structural and architectural solutions.[4]
- *Gradation of material and element properties:* variations within 3D elements (i.e., graded structures) can be produced using AM techniques. Such differentiation within a building component can be realized either through the variation of the geometry of a monolithic element or the pointwise variation of the material composition.[4]
- *Functional and topological optimization of structural and non-structural components:* it is easy to control the position of materials and integrate functional details or openings for building services. Building components optimized for the flux of force or for requirements of buildings physics can be realized with AM at the same cost as standard ones.[5,6]
- *Reduction of material waste:* AM allows for the reduction of formworks and supporting structures that corresponds to up to 60% of the total cost.
- *Safety in construction workplaces:* AM can reduce the risk of injury and death on workplaces thanks to automation of the construction process, the possibility of carrying out dangerous work without human intervention i.e., in case of high scaffolding, aggressive environments or hard to reach positions.

In order to benefit from the advantages that AM can provide to the construction field, further studies on the available AM technologies and materials suitable to be used are necessary. The most important challenges to deal with are the following: the transfer of AM technologies from small to large scales, the need of new and diversified materials, the development of constitutive models and computational processes apt to new design and structural optimization techniques as well as new technological systems and innovative assembling methods, the definition of new professional figures and of specific technical regulations and standardized quality processes.[7,8] AM processes can be divided into seven categories as described into ISO/ASTM 52900–2017: they are summarized in Table 1. The processes of Material Jetting, VAT photopolymerization and Sheet Lamination are not mentioned in the table because there are no known applications for the construction industry.

2 | AM TECHNOLOGIES APPLIED TO THE CONSTRUCTION INDUSTRY

AM systems have been developed mainly for small-scale applications and factory production. The buildings or building components are often large and it is often necessary to realize them out of a controlled environment; some of AM systems were adapted, which led to several different solutions. In fact, the greatest challenge facing additive construction is the transfer of AM technologies to large scale. In Table 2 the main AM solutions and principal projects currently realized and under study for the construction industry, are summarized and classified according to material type, AM processes and raw material.

In this section the current technological solutions for the construction field are described.

- Gantry system consists of a giant 3D printer where the printing head is attached on a movable frame that has three degrees of freedom according to X, Y and Z axis in Cartesian coordinates. This solution is relatively cumbersome to install. The main processes that are based on this system are material extrusion and binder jetting. Instead, powder-bed fusion process is used for metals and polymers materials.
- Cable-suspended platform is alternative to gantry solutions where the transportability of the system is improved. This system is composed by end-effector attached to an external frame through cables and its movement is controlled by motors.[8] With this solution it is possible to solve problems related to the size of the objects to be produced, which are bound to the size of the printer. Moreover, cable robots are relatively inexpensive and are easy to disassemble, transport and reassemble.[41]
- Swarm technique rejects the use of a single frame, in favor of several smaller mobile robots. This solution reminding a swarm behavior, embraces the approach of collective work. One of the advantages of the swarm approach is the total freedom during the construction and the need of no human physical intervention. Swarm approach is highly

TABLE 1 AM solutions for construction industry

AM process	AM type	Raw material	Construction industry: Gantry		Cable-suspended		Swarm	Robotic arms	
Material extrusion	FDM (FFF)	Solid viscous	CC[9] 3D concrete printing CONPrint3D[10] Total Kustom 3DCP[11] COBOD[12] Betabram[13]	BAAM[14] KamerMaker + DUS Architects[15] BLB[16]	WASP[17] FALCON-7[18] C4 Robot[8] SpiderBot[19] SkyPrinter[20]	Minibuilders[21] Neri Oxman[22] Quadcopter[23]	Minibuilders[21]	ATHLETE[24] DCP[25] ROB Technology; ETH Zurich; Gramazio & Kolher[26,27] Shotcreate TU Braunschweig[28] XtreeE[29] Cybe[30] Apiscop[31] Vertico[32] Arup[33]	C-FAB[34] DCP[25] Ai-build[35] FreeFAB[36] CEAD[37]
Binder jetting	BJ	Powder	D-shape[38]						
Powder-bed fusion	DMLS, SLM, SLS, SHS, EBM	Powder		Arup[39]					
Directed energy deposition	LENS, EBAM, WAAM, LMD	Powder						MX3D[40]	

Note: [grey], aggregate-based materials; [yellow], metals; [blue], polymers.

Abbreviations: BJ, binder jetting; DMLS, direct metal laser sintering; EBAM, electron beam additive manufacturing; EBM, electron beam melting; FDM, filament deposition modeling; FFF, fused filament fabrication; LENS, laser engineering net shaping; LMD, liquid deposition modeling; SHS, selective heat sintering; SLM, selective laser melting; SLS, selective laser sintering; WAAM, wire arc additive manufacturing.

TABLE 2 Classification of several methods of reinforcement for structures or elements printed

Typology		Matrix material	Reinforced material
External reinforcement		Concrete 3D	Steel
		Shotcrete concrete	Steel
Internal reinforcement	Lost formworks	Concrete	Steel
	Temporary formworks	Concrete 3D	Steel
Internal reinforcement during the process		Concrete 3D	Steel
Fiber reinforcement	Adding in mixture	Concrete, raw earth	Steel, carbon fiber, natural fiber
	During the process	Concrete, raw earth	Steel, carbon fiber, natural fiber
Additively manufactured reinforcement		Concrete 3D	Steel WAAW

beneficial in extra-terrestrial environments like space, Moon or Mars because it is possible to arrive and built where humans cannot.[42]

- Robotic arms are an efficient alternative solution to build buildings or components because each limb has six or seven degrees of freedom and an only robotic arm can perform different tasks, also additive construction. Therefore, it is possible to realize an entire building or its components with multi-purpose robotics solutions combined with automated assembly solutions, using additive construction on-site and off-site or also prefabricated parts.
- Folding and self-assembly solutions is a combination of deployable or self-assembly design with AM technology called Assembled Additive Manufacturing (AAM). It is possible to transform 3D structure into a 2D deployable structure, increasing the manufacture speed. These types of applications and solutions adds to 3D space another variable, the time. An object can be manufacture in 2D or 3D dimensions and later can transform its geometry over in time.[43]

3 | MATERIALS

The choose of AM technology closely depends on the materials being handled. With regard to the materials used for the construction industry this report focuses on aggregate-based materials, metals, polymers. A common example of aggregate-based materials used in the construction field is concrete. The principal AM processes for printing concrete are material extrusion and particle-bed processes but there are also other approaches like Smart Dynamic Casting and different systems are used to integrate reinforcements to balance the low tensile strength of concrete. Regarding material extrusion process there are specific characteristics necessary for concrete mixture to build a concrete element.[44] An important aspect for these processes is the filament size for the concrete extrusion.[45] This process is repeated to build layer by layer until the element is not complete. Post-processes can be necessary to increase strength and durability of the printed element, examples are heat treatment and infiltration. The advantages of particle-bed process consist in a more freedom of design because the non-bonded particles support the element to be built such as in case of cantilever beam. The limit of particle-bed process is the size of the object. For structures based on aggregate-based materials (i.e., concrete printed) is often important to use reinforced to improve their properties. There are several systems of reinforcement and it is possible to rank them according to whether the reinforcement is external, internal and whether it is installed after, during or before the deposition.

Regarding use the metals in AM there are steel, titanium, and its alloys, and also aluminum alloys, copper and many other. The processes to print metal parts are powder-bed fusion and directed energy deposition. Powder-bed fusion processes allow for high precision and geometry accuracy and, also, good mechanical properties. They are mainly used to produce small parts.[46] Direct Energy deposition is generally faster than powder-bed fusion and it can manufacture larger elements. Moreover, it can be used to repair existing parts. In the production of metal objects AM, a very low porosity is necessary that can be controlled calibrating input energy. Moreover, the microstructure and, hence, the mechanical properties, are anisotropic. In most cases, the direction perpendicular to the plane of deposition is the weakest.[47] Instead, fatigue strength can worsen due to material defects like residual porosity and by a coarse surface resulting from the layer-wise production process and it can be faced with post-manufacturing as heat treatments and hot isostatic pressing. The surface roughness can be reduced by successive polishing or chemical treatments.

Mechanical properties of 3D-printed metal parts and microstructure have been discussed in.[46,47] The most important aspects to improve and investigate the use of metal AM in construction field are topological and functional optimization and improvements of metal AM techniques.

Polymers for AM can be found in the form of thermoplastic filaments, reactive monomers, resin or powder. The AM processes to print polymers are principally two: material extrusion and powder-bed fusion. With the first technology it is possible to manufacture small and large elements, instead with powder-bed fusion is possible to manufacture small elements with a high accuracy.

4 | CONCLUSION

After describing all AM processes and solutions ever applied in the construction field, it is possible to get a complete overview to compare them. With Gantry systems and cable-suspended systems one can print buildings in one piece but the dimension of the object to be made depends on the size of the frame. Swarm systems is of great interest, but further studies and research are necessary to obtain real applications; currently, they remain confined to the field of experimental application. On the contrary, the use of robotic arms is upcoming in the construction industry because the technology is mature enough; this process allows to combine different materials and to change shape and properties during the construction process. Moreover, it is possible to combine the additive construction process with an automated assembly of elements. Finally, folding and self-assembly is a promising technique to manufacture buildings and building components, because the print into 2D dimensions is a proven technique; the possibility of self-assembly and changing over in time is promising.

In conclusion, all these AM technologies can be used in the construction field, but the choice of one rather than another should depend on the specific application, and the direction that this research field will take can hardly be foreseen.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable; no new data were generated.

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